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Proceedings of the

SPACE STATION EVOLUTION WORKSHOP

held at

Hilton National Conference Center
Williamsburg, Virginia

under the direction of

Office of Space Station
NASA Headquarters
Washington, DC

September 10-13, 1985

PREFACE

A four-day Space Station Evolution Workshop was held in Williamsburg, VA on September 10-13, 1985. The purpose of this Workshop was to survey potential Space Station growth modes in order to develop an initial understanding of their possible effects on the Initial Orbital Capability (IOC) Space Station design and on future technology requirements. Once this understanding is achieved, the Space Station development team will be in a better position to determine which "scars" should be incorporated into the IOC design, and which technology developments should be undertaken.

Dr. David Black, the Space Station Chief Scientist, served as the Workshop Chairman. In order to ensure that a broad range of NASA expertise was represented at the Workshop, participants were drawn from the Space Station Program and other NASA programs. Each participant serving on the Workshop was selected because of his or her specific background in areas considered vital to the success of the Workshop. A Steering Committee was also formed to oversee the activity and provide a real-time response to the Workshop findings. The Steering Committee members were selected from NASA Headquarters and Center management personnel and the Committee was chaired by Capt. Robert F. Freitag, Director of the Policy and Plans Office of Code S at NASA Headquarters.

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WORKSHOP MEMBERSHIP

Chairman:	Dr. David Black
Executive Secretary:	Ms. Barbara Askins
Members:	Mr. Richard Baillie Mr. Jerry Barna Mr. Gene Beam Mr. Marc Bensimon Mr. John Butler Mr. Dennis Fielder Dr. Ken Frost Mr. Harry Guin Dr. Dana Hall Maj. Paul Heartquist Mr. Ray Hook Dr. Earle Huckins Dr. Joe Kerwin Dr. Tom Labus Dr. Henry Lum Mr. John Niehoff Ms. Donna Pivirotto Mr. Brian Pritchard Dr. Robert Ried Mr. Lorne Robinson Dr. Glenn Smith Ms. Mary Jo Smith Dr. Edwin Speaker Mr. Lee Tilton Mr. William Tumulty
Conference Coordinator:	Ms. Carolyn Kimball
Secretaries:	Ms. Karen Ford Ms. Valerie Young Crockett

SPACE STATION EVOLUTION WORKSHOP

EXECUTIVE SUMMARY

In the summer of 1985, the Space Station Program was beginning the Phase B definition process, dedicated to developing the designs and technologies required for the initial Space Station. A major design criterion was, and continues to be, that the Station be capable of evolving on orbit to greater capacities and capabilities, as driven by user requirements. Therefore, specific evolution provisions, commonly referred to as "scars," are being incorporated into the basic design. The Phase B evolution design requirements are based on the assumption that the Space Station will eventually evolve to provide the resource levels and other capabilities specified in the Space Station Functional Requirements Envelope (FRE). The Phase B evolution Space Station reference concept for meeting these requirements focuses primarily on *in situ* growth, i.e., a larger version of the initial Space Station with increased power and other resources plus accommodations for an Orbital Transfer Vehicle and related propellant resupply facilities.

While the FRE and the evolution reference concept represent the best possible evolution planning based on currently available data, the Space Station Program realizes that many factors could change the emphasis of the requirements before the evolution phases are implemented. For example, commercial investigations could lead to a greatly expanded demand for Earth observations, or the national response to the National Commission on Space Report could lead to a major new initiative such as a Lunar Base or a Manned Mars Mission. The Space Station should be designed to serve as a stepping-stone to any space endeavors that this nation and its international partners choose to undertake. Although it is not possible to incorporate specific "scars" for all potential future endeavors, the Space Station Program should understand their general implications and attempt to design an initial Space Station that will facilitate their implementation.

The Space Station Evolution Workshop was convened in September, 1985 to begin to develop a broader understanding of potential evolutionary paths and their implied requirements on the Space Station Program. To pursue this objective, the Workshop was organized to investigate specific "scenarios" for the Space Station evolution phase. Workshop teams were constituted to develop an initial understanding of the user requirements, major systems issues, technology development needs, and policy implications of these scenarios.

The requirements teams started with the Space Station User Data Base and added potential new requirements as appropriate for the evolution scenarios. The evolution emphasis teams developed concepts for the growth of the Space Station to accommodate the evolution scenarios. All teams identified required systems issues, technology development requirements, and policy questions related to their areas of investigation. The results were consolidated by three teams that developed composite lists of: growth concepts, near-term trade studies and impacts on the initial Space Station; requirements for technology development and scars for future technology upgrades on the Space Station; and policy implications of the evolution scenarios.

In addition to the team meetings, each day of the Workshop included a plenary session for each team to discuss its findings with the other teams. One important conclusion derived from the plenary session discussions was that operational conflicts will become numerous as the Space Station evolves to meet diverse user needs. If, for example, the amount of time and space that is devoted to microgravity processes is required to increase at the same time that Orbital Transfer Vehicles are based at the Manned Element and satellite servicing requirements increase, the requirement to maintain the microgravity level will be in conflict with the requirement to service and deploy satellites. **Concern about these potential conflicts led the Workshop to emphasize the concept of "branching."** This concept suggests that user support functions will be divided into operationally compatible groups, and in the evolutionary phase each group will be accommodated on a specific infrastructure element. For example, transportation node functions, including satellite servicing, might be accommodated on a Manned Element, while precision pointing and microgravity functions could be accommodated on platforms or on a replicated Manned Element.

The evolution concepts developed by the Workshop teams addressed growth in both the platforms and the Manned Element. Regarding platforms these concepts anticipated increases in the number of platforms and the expansion of their uses. For example, one scenario for the accommodation of increased materials processing facilities was to create free-flying platform "factories" that are serviced from the Manned Element.

The evolution concepts for the Manned Element included growth of the Initial Orbital Capability (IOC) Station, as in the reference concept, and several options for branching. These options generally centered around the objective of dividing activities preferring a benign environment (e.g., micro-g research and fine pointing experiments) from those creating a dynamic environment (e.g., servicing, staging, and deployment of satellites). Concepts for growth to accommodate a major new initiative, such as a Lunar Base or a Manned Mars Mission, were difficult to develop because the detailed requirements for these missions have not been defined. Based on its own scenarios for these missions, the Workshop concluded that extensive accommodation of these missions would cause major conflicts with existing user requirements on the Manned Element; therefore, some form of branching would be required to simultaneously accommodate a major new initiative and existing user requirements.

The Workshop technology team identified technologies that need to be developed to enable or enhance the execution of the evolution scenarios. These technologies were catalogued by discipline and by infrastructure element. **Automation and robotics technology was identified as a primary driver for major aspects of all scenarios.** The team also identified areas where technology insertion is likely and recommended that the initial Space Station be designed to facilitate the insertion of such technologies.

The Workshop policy team identified a number of policy issues relevant to Space Station planning for the evolution phase. These included: technical issues (e.g., manifesting of the National Space Transportation System); questions about international agreements; operational issues including questions about public access to the Space Station; and budgetary issues.

Finally, the Workshop identified and recommended a number of specific trade studies or analyses that are important to developing a viable evolution program for the Space Station. These are detailed in the text. Two major themes emerged strongly from the Workshop. One is that the concept of branching, arising from operational incompatibility among users, may be the dominant consideration in evolution planning. This is a new concept as applied to the Manned Element and should be a principal focus of future evolution studies. The second major theme highlights the potential of technology upgrades as a key mode of evolution, with particular emphasis on automation and robotics. Further study of these themes is expected to establish their feasibility and provide important direction to the continued planning for Space Station growth.

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1. INTRODUCTION

Traditional NASA flight projects have always been a complete hardware expression of their design objectives at the time of launch. While it is true, particularly for launch vehicles, that recurring fabrications of given concepts often incorporate improvements from one flight to the next, each individual system ceases to evolve once it is launched. In this regard, the Space Station initiative represents an entirely new approach to space system development. It will not even represent an operating system until it is assembled on orbit, and its initial operating capability will become a point of departure for growth as the Space Station user community evolves. Hence, planning of the Space Station will be a continuing effort which must anticipate future growth, prudently integrating into current design work "scars" which will readily enable accommodation of such growth when it becomes desirable and/or necessary.

The purpose of the Space Station Evolution Workshop was to survey potential Space Station growth modes in order to develop an initial understanding of their possible effects on the Initial Orbital Capability (IOC) Space Station design and on future technology requirements. It is expected that once this understanding is developed, NASA will be in a better position to decide which "scars" should be incorporated into the IOC design. This document represents a preliminary statement of this understanding.

2. WORKSHOP APPROACH AND ORGANIZATION

The Workshop was organized with three evolution-related objectives in mind. These are:

1. To define prospective evolution modes which have major influences on the Space Station Program's ability to satisfy user needs.

2. To develop an initial understanding of the effect of these prospective evolution modes on the IOC Space Station.

3. To identify any advanced technological areas critical to these prospective evolution modes.

To address these objectives, the Workshop was organized into three sequential splinter sessions designed to guide discussion among the members. Within each session, teams were organized to address specific areas of that session's theme. Team membership within each session was reconstituted in order to ensure the broadest possible exchange of ideas between Workshop members and to provide each new team with participants from all previous teams. This arrangement involved all members of the Workshop in the process of synthesizing a consistent set of conclusions and recommendations. The Workshop also met in plenary sessions between each splinter session to review its progress toward the stated objectives of the effort.

The themes of the three splinter sessions and the subject areas of each session team are summarized in Table 1, which presents an overview of the Workshop approach. On the last day of the Workshop, its findings were presented to the Space Station Evolution Workshop Steering Committee. The Steering Committee members did not participate in the Workshop prior to this point, but they were involved in Workshop preparation and planning. Given their management background and experience, the Steering Committee was a valuable sounding board for initial reaction to the Workshop results. The Steering Committee members were also effective in assisting the Workshop members in identifying the highest-priority items within their findings and recommendations.

Table 1

SPACE STATION EVOLUTION WORKSHOP APPROACH

- **FIRST SPLINTER SESSION**

Theme: Refine and consolidate major requirements of potential growth areas, identify sensitivities, and begin development of evolution scenarios

Team A: Observations and experimentation which take place exclusively on a manned element

Team B: Usages of co-orbiting, polar, and/or geosynchronous platforms

Team C: Assembly, servicing, and staging from a manned element

- **SECOND SPLINTER SESSION**

Theme: Possible evolution modes in response to emphases; identification of major infrastructure elements; preliminary identification of trades, studies, and technology development

Team D: Growth emphasis on general increase in research and technology driven by Space Station user data base

Team E: Growth emphasis on increase in commercial activity including private services provided by private users

Team F: Growth through the adoption of a major new initiative such as a lunar base or manned Mars mission

- **THIRD SPLINTER SESSION**

Theme: Assimilation of findings with supporting rationale

Team G: Draft recommendations for near-term trade studies and impacts to IOC ("scars")

Team H: Draft recommendations for longer-term technology developments and identified "scars" for technology upgrades

Team I: Draft statement on policy implications of evolutionary plans

In the sections which follow, background information for the Workshop is presented, including "strawman" evolution scenarios that were posed to the membership. This is followed by brief synopses of each team's findings. The presentation of conclusions and recommendations to the Steering Committee is included in Section 5. Terminology which is used frequently in this document is fully defined in Appendix A. Memberships and affiliations of the Workshop and Steering Committee participants are included as Appendix B.

3. BACKGROUND INFORMATION

Three specific areas of background information were presented to the participants at the outset of the Workshop in order to establish guidelines for the subsequent discussion of Space Station evolution. These were: (1) the Functional Requirements Envelope for the first ten years of Space Station operation; (2) the IOC Reference Configuration; and (3) Strawman Evolution Scenarios to guide team discussion. Each of these information areas is briefly summarized in the subsections which follow.

3.1 Functional Requirements Envelope

The Functional Requirements Envelope (FRE) is an evolving statement of user-dedicated Space Station capabilities which serves as an effective performance goal to guide the initial definition of the Space Station. It does not include overhead for the maintenance of the Station itself. The definition of the FRE given to the Workshop members superseded the user requirements as stated in Appendix C-2 of the Phase B RFP, which, in turn, was a broader statement than the reference configuration capabilities given in Appendix C-4 of the RFP. However, the FRE itself is expected to be superseded by a performance envelope to be established after the Interface Requirements Review (IRR), which will specify Space Station IOC design requirements. Even so, definition of the FRE, both at IOC and ten years post-IOC, provides valuable insight into the pressures for Space Station evolution caused by anticipated growth in user numbers and demands.

User communities representing applications, commercial, operations, science, and technology fields have all expressed an interest in using the Space Station. A brief summary of disciplines for which various sponsors have shown an interest is presented in Table 2. These user desires are included in a Space Station User Requirements Data Base for the first ten years of Station operation. The data base covers every identified class of user activity through the year 2000; it is expected that major driver missions, such as a Manned Lunar Base or a Manned Mars Mission, will be added to the data base when more detailed information on these initiatives is available.

Table 2

TYPES OF ANTICIPATED USAGE BY SPONSOR

Discipline	Canada	ESA	Japan	NOAA	NASA OAST	NASA OCP	NASA OSSA
Astronomy	●	●	●				●
Earth Observations	●	●	●	●			●
General Commercial		●	●			●	●
Life Sciences	●	●	●				●
Materials Production		●				●	●
Materials Research and Development	●	●	●		●	●	●
Planetary Research		●	●				●
Solar Terrestrial Research	●		●				●
Technology Development and Demonstration	●	●	●		●		

Acronyms:

ESA - European Space Agency
NOAA - National Oceanic and Atmospheric Administration
OAST - Office of Aeronautics and Space Technology
OCP - Office of Commercial Programs
OSSA - Office of Space Science and Applications

Even with the removal of similar requirements from multiple users and adjustments for realism, user expectations remain high. This is readily apparent in Table 3, where major Space Station parameters are summarized per C-4, C-2, and again late last spring, both for IOC and ten years post-IOC.

Functional Requirements Envelopes (FRE) of each of the three Space Station elements were specifically defined for the Workshop and are briefly summarized here. For polar platforms, the resources available to users on a single platform, as defined in Table C-2-1 of Appendix C-2 of the Phase B RFP, were assumed to be equivalent to the FRE. Each platform was further assumed to have a non-service lifetime of three years, with scheduled servicing intervals of two years. For evolution discussions, two polar platforms (one provided by NASA and the other by ESA) were assumed to be in service at IOC, increasing to four platforms by the mid-1990s and reaching a total of six platforms by the year 2000.

Co-orbiting platforms, the second infrastructure element, were assumed to have an FRE also as given in Table C-2-1 of Appendix C-2 of the RFP, but which includes only those resources available to support astronomical payloads. The Workshop participants were to consider whether or not these platforms could also support materials production payloads, given the following capabilities: (1) sustained low acceleration levels ($\leq 10^{-5}$ g); and (2) minimum average electrical power of ten kw. The advantage of raising platform power to 20 to 30 kw was also to be addressed. No guidelines on the number of co-orbiting platforms were given; rather, each Workshop team was charged with seeking its own determination of this requirement.

Requirements for the final and largest element of the infrastructure, the Manned Element, were discussed in some detail. Here FRE guidelines were expressed in terms of eight parameters: (1) STS launches; (2) average electrical power; (3) average data rate to ground; (4) pressurized volume; (5) user crew; (6) extravehicular activity (EVA) hours; (7) number of attached payloads; and (8) Orbital Maneuvering Vehicle (OMV) events. These requirements and their growth rates, as presented to the Workshop, are summarized in Table 4 for a period of ten years, beginning at IOC. All eight parameters

Table 3

SUM OF USER REQUIREMENTS

	Major Parameters					
	IOC			IOC + 10 Years		
	C-4	C-2	5/1/85	C-4	C-2	5/1/85
Co-Orbiting Platforms						
Number	1	1	Small Demand	1	1	Small Demand
Polar Platforms						
Number	1	1	3	1	1	12
Manned Element						
Average electric power (kw)	50	75	123	250	221	375
User crew	6*	6	14	18*	12	27
Pressurized volume (m^3)	45-90	123	169	180	300	405
Payload launches per year (dedicated STS)	-	5	14	-	5	12

*Total Crew

Table 4

FUNCTIONAL REQUIREMENTS ENVELOPE: MANNED ELEMENT USERS ONLY[1]

Year	1	2	3	4	5	6	7	8	9	10
STS Launches[2]	4	6	9	12	12	13	14	14	11	9
Average Electrical Power (kw)	80	85	155	245	290	290	340	375	375	375
Average Data Rate to Ground (mbps)	20	75	140	160	165	145	165	145	160	135
Pressurized Volume (m^3)[3]	120	125	200	270	295	300	325	325	325	330
User Crew[4]	10	11	14	17	18	18	17	18	20	20
EVA Hours[5]	412	368	462	509	810	915	1504	780	820	794
Number of Attached Payloads	14	15	12	13	15	18	15	14	15	13
OMV Events[6]	6	12	24	24+	24+	24+	24+	24+	24+	24+

1. All parameters are for resources available to the user and do not include "overhead."
2. In addition to use of 6,000-kg payload allocation on each of four logistics modules a year. Assumes launches of 15,000 kg capability dedicated to payloads. Does not include overhead such as launch of additional modules, OMV fuel, etc.
3. Multi-user laboratory volume required for users' instrumentation. Does not include habitation volume or privately supplied volume dedicated to a single user.
4. Assumes nine hour work day and six day week. Assumes user crew will perform payload-associated EVA and RMS and OMV proximity operations.
5. Productive EVA work hours. Not additive. Crew required to perform EVA included in "user crew" totals.
6. Number of assembly, servicing, and staging events to be supported by OMV. May require two OMV round trips for some events. Capability should be increased as rapidly as possible.

represent resources available to the user and do not include overhead. Each STS launch is assumed to have a 15,000-kilogram capability dedicated to payloads. This does not include 6,000 kilograms per logistics module per year for resupply, nor does it include such overhead items as additional modules, Orbital Maneuvering Vehicle (OMV) fuel, etc. The volume figures given in the table are for the multi-user laboratories only. Habitation and dedicated single-user volumes are not included in these values. User crew size is based on a nine hour per day, six day per week work schedule and includes payload-associated EVA and Remote Manipulator System (RMS) tasks, as well as OMV proximity operations. OMV events include assembly, servicing, and staging tasks, and may require several round trips to complete certain tasks. OMV capability should grow as rapidly as possible. The guideline FRE resulting from these data is summarized in Table 5, both at IOC and ten years post-IOC. For reference, C-4 and C-2 capabilities are also shown. Pressurized volume, average power, data to ground, and user crew size are forecast to grow over the first ten years of Space Station operation by factors of two (for crew) to six (for data).

Table 5

MAJOR PARAMETERS OF THE MANNED ELEMENT

			IOC		IOC + 10 Years
	C-4	C-2	Recommendation	C-2	Recommendation
Average Electrical Power (kw)	50	75	80	221	375
Data to Ground (mbps)	--	29.1	20*	52.5	135*
Number of Attached Payloads	9	9	14	9	13
Pressurized Volume	45-90	123	120	300	330
User Crew	6**	6	10	12	20
STS Launches	--	5	4	5	9

* Includes video
** Includes Station operating crew

3.2 Space Station IOC Reference Configuration

The reference configuration of the Space Station system used at this Workshop consists of several components, including a permanently occupied Manned Element with a space-based Orbital Maneuvering Vehicle (OMV), and free-flying platforms co-orbiting with the Manned Element and in polar orbit. These components complement each other in carrying out the tasks identified for the Space Station system. The Manned Element can be further subdivided into segments including the external truss structure, pressurized modules, the power system, attitude control and propulsion systems, thermal control, and payload accommodations.

The NASA reference configuration for the Manned Element at the time of this Workshop was the "Power Tower"; however, the Manned Element was being reassessed with serious consideration being given to the "Dual Keel" configuration. Therefore, the Power Tower is described in some detail in this section as the reference configuration for Workshop discussion. The Dual Keel is described further at the end of this section.

The overall configuration of the Manned Element is defined by the structure which ties all of the elements together. As illustrated in Figure 1, this structure consists of a single vertical member, known as the "keel," which is 121 meters in length, along with three horizontal members. The top and bottom horizontal members both provide approximately 90 meters of length for the support of Earth viewing and deep space viewing payloads. The central horizontal member, 80 meters in length, provides support for the power system solar energy collecting panels and thermal radiators. The individual cells of the truss network will measure five meters on each side and will be assembled by EVA.

The Station crew will be housed and will conduct experiments in four pressurized commmon modules mounted at the nadir end of the keel. These common modules are 9.1 meters in length and 4.4 meters in diameter. Each module will connect with two other modules to form a continuous loop, or "racetrack," which allows the crew two avenues of escape in case of emergency. One of the modules is outfitted as a materials and technology laboratory while

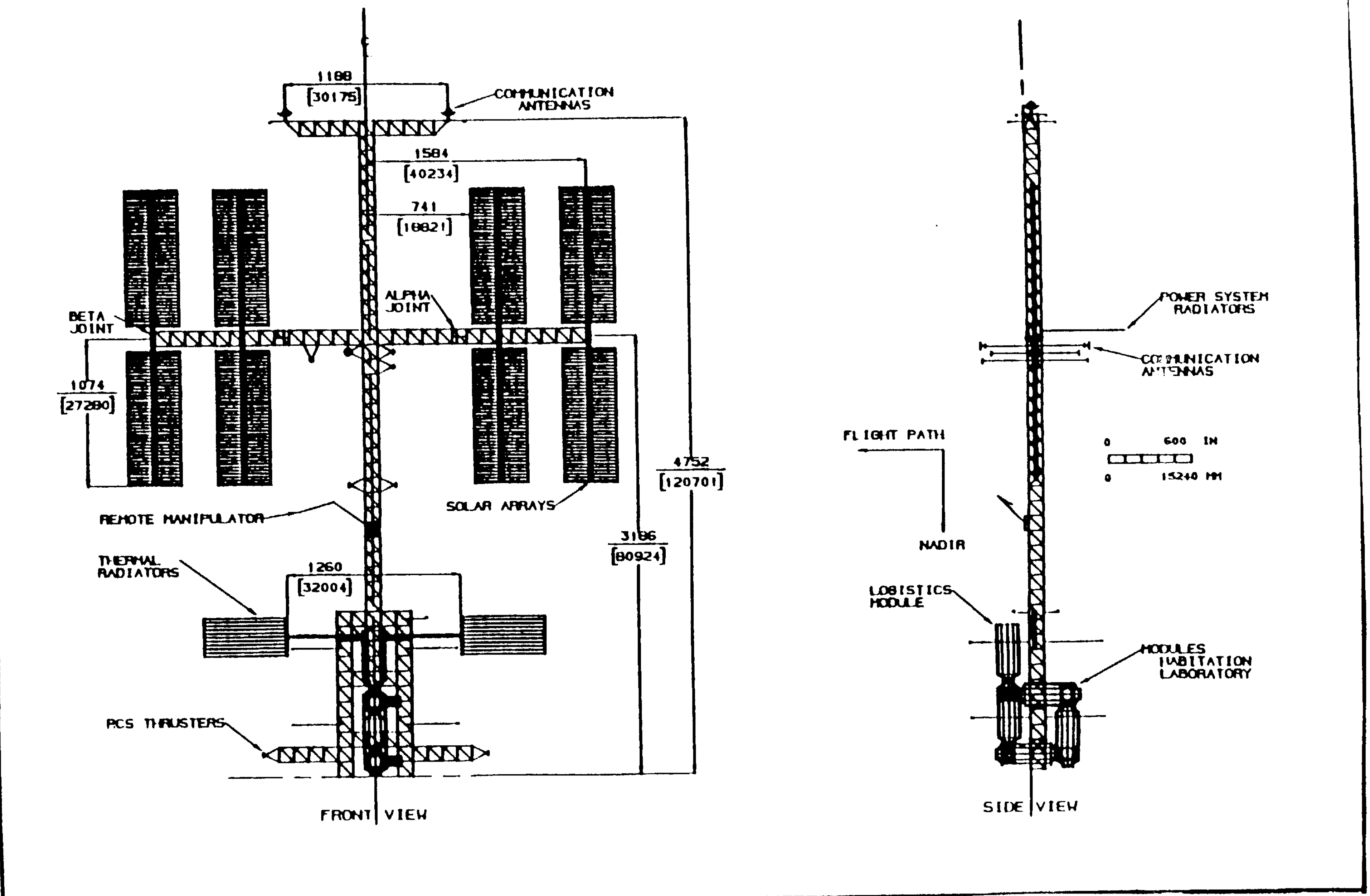


Figure 1. Manned Core Space Station Reference Configuration

a second is configured as a life sciences laboratory. Both are used to conduct basic research on orbit. Crew quarters and Station controls will be housed in the remaining two modules.

The crew and Station consumables will be resupplied every 90 days. This will be accomplished through the use of a logistics module which will be attached to one of the docking adapters of the racetrack. Non-fluid expendables, orbiter spares, and experiments housed in standard racks will be contained in the pressurized portion of this module, which is located closest to the crew module for ease of crew access. Fluid resupply will be contained in an unpressurized aft-mounted section with appropriate transfer lines to the Manned Element.

The power system is primarily located at the outboard ends of the central horizontal structural member. As shown in Figure 1, this system consists of four large solar arrays which provide a total of 75 kw of power. The solar arrays provide all daylight needs, including the regeneration of an energy storage system used to power the Station during those periods when it is in Earth's shadow.

Pointing and attitude control for the Space Station will be provided by double gimbaled control moment gyros (CMGs). The sensors for these actuators consist of rate gyros, star trackers, and accelerometers. This system is provided to augment the inherent gravity gradient stability of the overall configuration. The backup to the CMG system is the on-board propulsion system. However, the main function of the propulsion system is to overcome the small but steady loss of orbital energy caused by atmospheric drag. This system consists of four thruster clusters located at the ends of the upper and lower horizontal structural members. Propellant is supplied from a storage system on-board the Manned Element and from tanks located in the logistics module.

Thermal control will be provided by a combined system of localized and centralized cooling loops. Each pressurized module has its own thermal control system, sufficient to provide cooling to that module should it be used as a safe haven during an emergency. Cooling in excess of these needs will be provided by the centralized system using a set of gimbaled radiators located just above the racetrack for heat rejection. A separate cooling system is provided for the electrical generating system.

Accommodations for externally mounted payloads will be provided along the upper and lower horizontal members and along the central vertical keel. The upper and lower structural members provide the best view of Earth and deep space. The central keel will be used in growth scenarios for storage and servicing of various spacecraft, Orbital Transfer Vehicles (OTVs), and the OMV.

The unmanned platform elements of the Space Station system are used to complement the activities occurring on-board the Manned Element. In this role, the platforms will act as a support core for a variety of different missions, including scientific investigations, technology development, and commercial applications.

The basic configuration for the platform is shown in Figure 2. This configuration represents the core support vehicle without an attached payload. The design philosophy used to develop this configuration assumed commonality with the manned Space Station elements to the greatest possible extent. All subsystems are assumed to be modular and use the same interfaces as the Manned Element. All of these factors improve the maintainability and repairability of the system, along with providing the opportunity to upgrade subsystems over time. This also facilitates the direct transfer of subsystems or payloads between the Manned Element and the platforms.

The unmanned platforms are designed to operate in the same orbit as the Manned Element and in polar orbit. This latter capability limits the IOC mass of the platform, its payload, and other associated equipment to less than 9000 kg, due to the Space Shuttle's capability for polar launches. The core vehicle is able to supply five kw of power in its IOC configuration with a growth capability for larger payloads envisioned. This platform also provides for a variety of pointing options, such as inertial or solar.

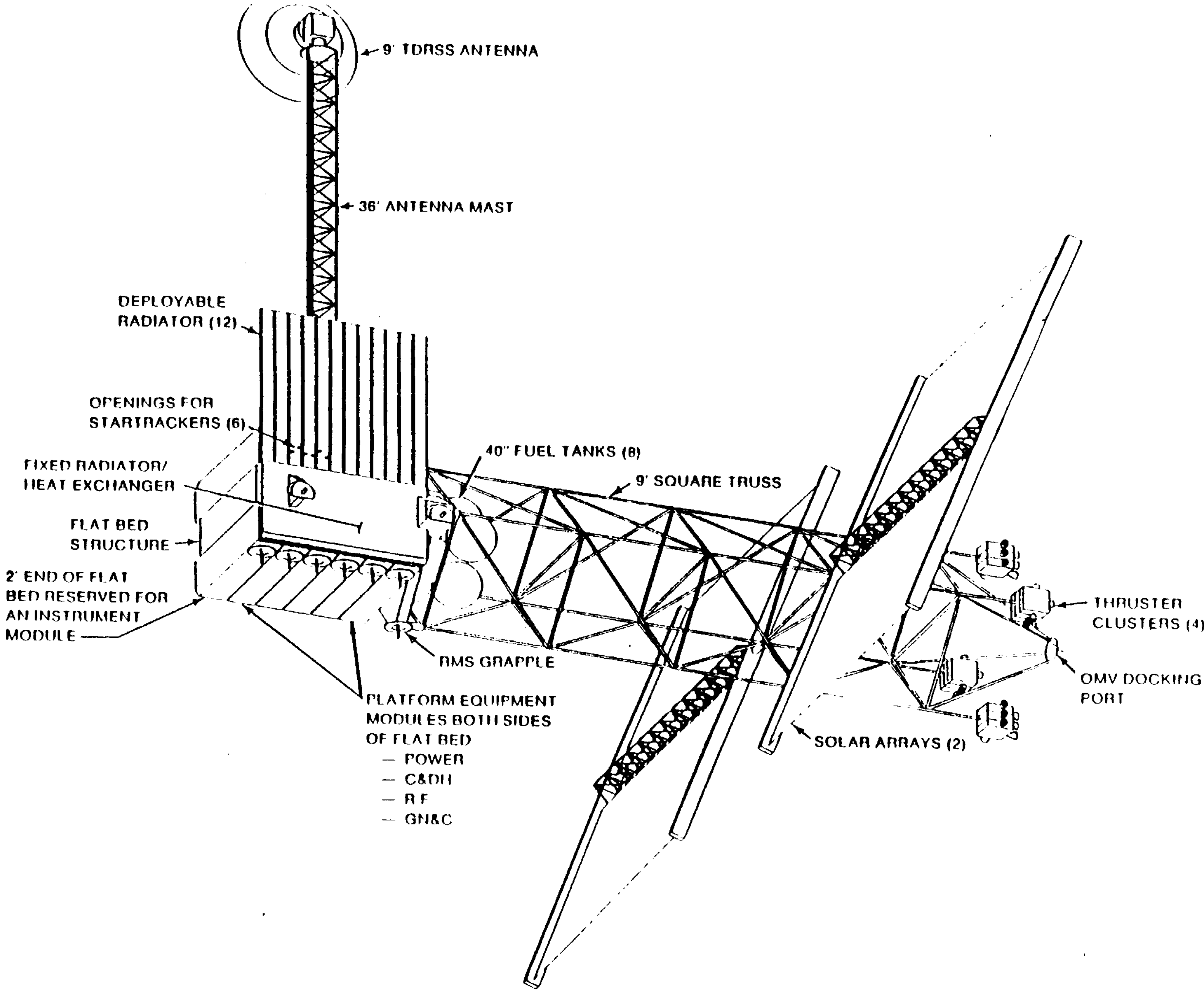


Figure 2. Space Station Core Platform (without Payload)

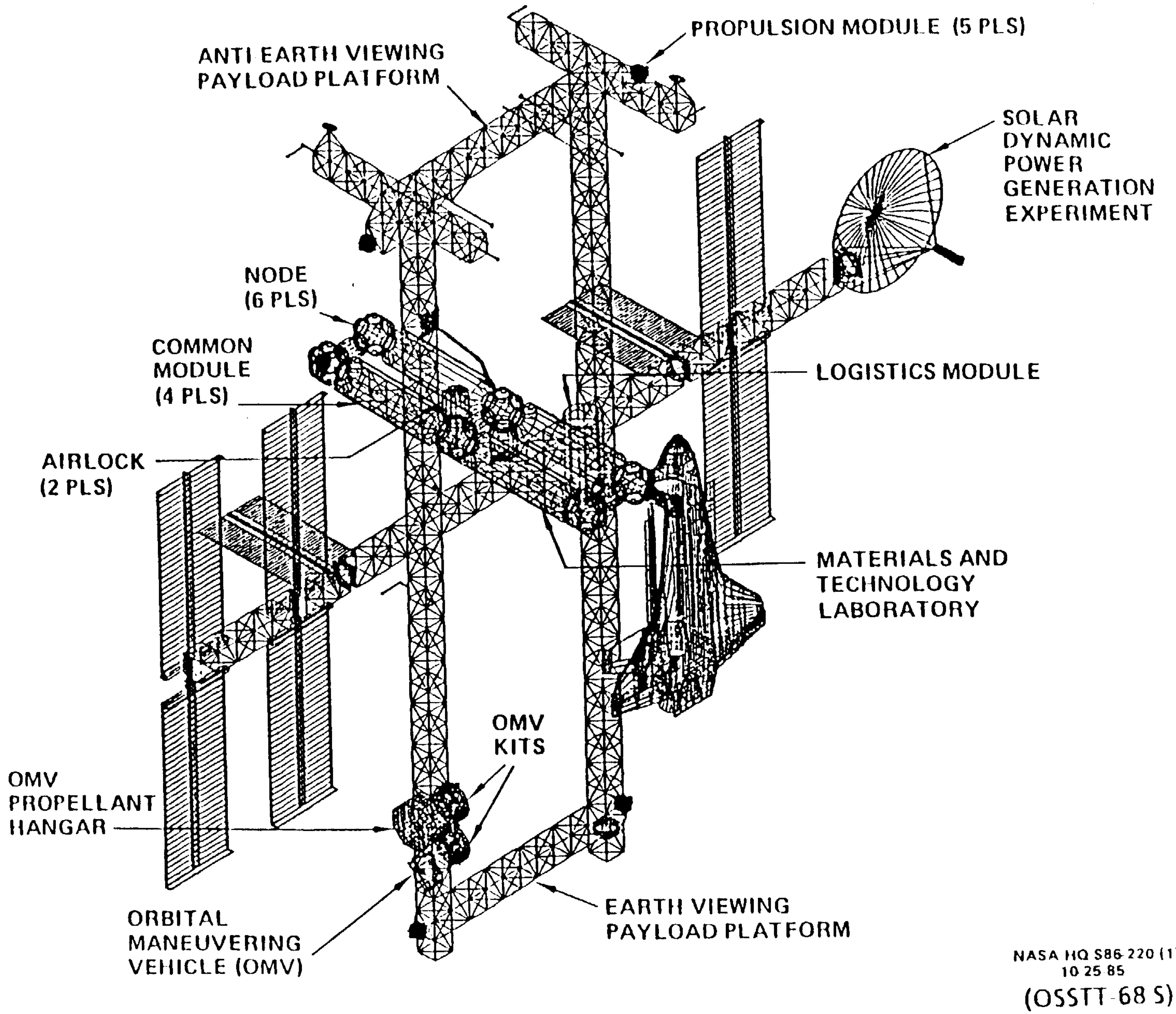


Figure 3. Space Station Dual Keel Arrangement

At the time this Workshop was under way, recommendations from the Phase B study contractors indicated that a change to a "Dual Keel" configuration would better satisfy the needs of the Space Station system as they are presently understood. This configuration is illustrated in Figure 3. As can be seen, all major components discussed above still exist in this option but in some cases the location has been changed. The advantages offered by this configuration include more area for future growth and attached payloads as well as location of the Materials and Technology Laboratory closer to the Station center of gravity for a more stable microgravity environment.

3.3 Strawman Evolution Scenarios

Strawman scenarios of Space Station evolution were posed to the Workshop members to stimulate the definition of growth requirements and the creation of evolution modes in response to specific growth emphases. Three scenarios were presented, each requiring an alternate evolution of the Space Station infrastructure. Each scenario was based on a specific set of user requirements which were assumed to be the prime motivation for sustaining a Space Station growth phase. The emphasis in each of the three scenarios is described as follows:

1. **Research and Technology Evolution Scenario**

   This scenario assumes that the major requirements for the post-IOC Space Station are determined by a continued increase in science, technology, and commercial experimentation facilities as anticipated by the present user data base. Growth includes transportation to geosynchronous orbit (GEO) and other higher energy orbits from the Station, satellite servicing at GEO, and the assembly of large structures at the Manned Element, in addition to increases in the IOC research and technology.

2. **Commercial Growth Scenario**

   This scenario assumes that the success of initial Space Station experiments leads to substantial expansion of commercial activities, perhaps including "factories" in space. The possibilities include commercial Earth observations, satellite servicing, materials processing, and others. The emphases chosen for this scenario should be materials processing at low-Earth orbit (LEO) and commercial communications platforms at GEO.

3. **New Initiative Growth Scenario**

This scenario assumes that the National Commission on Space recommends, and the U.S. adopts, a major new initiative in space for which the Space Station is used as a transportation node. For evaluating this scenario, the initiative to be assumed should be either the establishment of a lunar base or the conduct of a series of manned Mars missions. The requirements and impacts of requisite unmanned precursor missions are to be included in this assessment.

A fourth scenario was also proposed for consideration, which was the evolution of the Space Station through technology upgrades only. This evolution mode would increase efficiency and productivity, permitting greater user accommodation within the same physical facilities. While this scenario was considered explicitly only by Team H, its advantages were assumed to be applicable to any of the first three scenarios, consistent with technology advancement.

For the purpose of developing infrastructure growth paths, and associated definition trade studies and technology requirements, each of the three scenarios was assumed to be independent. Commonality of infrastructure requirements, or the possibilities for accommodating more than one scenario at any given time were not of immediate concern to the Workshop participants. Rather, the identification of unique and common elements of the infrastructures derived from each scenario was the primary objective. The identification of prerequisite technology and critical design trade studies associated with the implementation of these elements in enabling infrastructure growth was also a major objective of the Workshop. The relative importance of various implementation options would be addressed by the Workshop in concluding its findings by assessing the utility (i.e., uniqueness versus commonality) with which each option served alternate growth scenarios. (Note that this assessment also addresses, therefore, the facility with which combined scenarios might be served by various infrastructure options.)

4. SYNOPSES OF WORKSHOP SPLINTER SESSIONS

As discussed in Section 2 of this report, the Space Station Evolution Workshop was organized into a series of sequential splinter sessions, each with a theme building on the previous session theme(s). Within each session, three teams of Workshop members were constituted to discuss and generate findings regarding specific elements of that session's theme. These discussions and findings are synopsized in the subsections which follow.

4.1 Session 1: Major Requirements for Growth

The objectives of the first session were to refine and consolidate the major requirements of potential growth areas, to identify infrastructure sensitivities to growth, and to begin the development of alternate evolution scenarios. The three session teams were organized to address the following: (Team A) - the Manned Element observations and experimentation; (Team B) - usages of co-orbiting, polar, and geosynchronous platforms; and (Team C) - assembly, servicing, and staging from the Manned Element.

4.1.1 Team A: The Manned Element

Team A was charged with addressing the growth requirements of the Manned Element to support observations and experimentation. To be included in their discussion were user disciplines including life sciences, materials research, technology advancement, astronomy, Earth observations, plasma physics, communications, and basic physics and chemistry.

The Team utilized existing customer requirements across these varied disciplines as its point of departure for growth. However, rather than discussing growth impacts discipline by discipline, the Team addressed growth of the Manned Element from three, more generic, directions represented by the following questions:

1. What new activities/physical elements would cause Manned Element growth?

2. What present capabilities, when increased, would specifically require growth?

3. What IOC design elements presently being considered might inhibit growth?

Regarding the first question, the Team accepted the growth requirements of the Space Station 10-year user data base and identified some potential new requirements:

1. A laboratory for hazardous research
2. Centaur staging at the Space Station
3. On-orbit technical services
4. Warehousing
5. Crew recreation
6. Accelerated manned missions technology research.

The addition of a laboratory for hazardous research would enable on-orbit studies in materials combustion ("fires"), genetics (biological engineering), and similar activities which possess intrinsic risks. It could also serve as a quarantine unit and a disposition center for end-of-life materials/systems. The overall risk such a laboratory might pose to the Manned Element could be a determining factor in its location; e.g., should it be attached, tethered, or co-orbiting?

A second item of growth interest was Centaur staging, which is as much an operational addition as it is a physical one. Fully loaded, the Centaur(G') upper stages utilize almost all of the Shuttle's payload capacity. To apply its full capability for orbital transportation with larger payloads (> 5000 kg), therefore, requires orbital integration. Using the Space Station as such an assembly or staging node would be a growth requirement. Impacts of concern include not only staging ports but also assembly requirements, payload manifesting, and propellant maintenance, as well as a host of other issues, e.g., pre-release checkout, venting, Station mass balance, and Station resources (power, thermal control, and manpower).

The possibility of a Space Station repair shop represents growth in on-orbit services aboard the Manned Element. Such a facility could include machine shop equipment and an electronics laboratory. With these capabilities, not only could significant repairs be accomplished on orbit, but the potential for innovative developments in servicing would be significantly enhanced. The ability to apply existing parts and materials to new applications and to accomplish difficult on-site repairs would be expected to improve the overall utility of the Space Station system.

Another idea for growth, coupled to the repair shop concept, is warehousing. Warehousing would provide the means for maximizing STS usage by bringing up extra materials and supplies on flights to the Space Station that would not otherwise be fully manifested. The underlying theme of both the repair shop and warehousing concepts is the maximum use of all materials brought to the Station. Even at only a few hundred dollars per pound (the cost objective of a Heavy Lift Launch Vehicle) the transportation costs to orbit greatly enhance the value of everything brought to the Station.

Crew recreation, while not ignored in the IOC design, is provided at a very basic level. With other Manned Element growth, hopefully crew lifestyle can also be enhanced with more recreational opportunities. Several ideas posed were: (1) a dedicated area for physical exercise as well as informal group meetings (movies, lectures, etc.); (2) recreational EVA; (3) personal televideo centers to visit with ground-based family and friends; (4) personal access to operational facilities for individual projects (hobbies); and (5) introduction of other living organisms into crew quarters, e.g., plants, fish, or pets. These are not meant to reflect well-thought-out ideas, but rather to represent a spectrum of possibilities to stimulate planning in the area of recreation.

A final area identified by the Team as an additional requirement was the accelerated on-orbit research in technologies associated with manned missions. If a national or international initiative were to be undertaken around the turn of the century to establish a lunar base or send men to Mars, it would certainly accelerate certain technology research aboard the Space Station. Though not inclusive, issues of research concern would include long-term weightlessness, biological effects of radiation, long-term reliability of critical components such as fuel valves, power sources, life-support systems, etc., increased levels of automation, psychological crew testing, and testing of new systems such as closed-loop life support and components for in situ resource production. The key point to note is that while many or all of these issues will probably be addressed as part of planned Space Station activities, the early national commitment to a manned mission initiative would undoubtedly accelerate the pace of Space Station research, which would in turn place growth pressure on the Manned Element facilities.

The second approach to growth assessed by the Team addressed areas of capability (or inability as the case may be) and included: (1) increased Station power; (2) increased man-years per year on orbit; and (3) increased operational conflicts resulting from broad-based growth. Beginning with increased power capability, three power sources, listed in order of technical difficulty and power-generating ability, were recognized: (1) photovoltaic, (2) solar dynamic, and (3) nuclear. Hence, if the power requirements grow significantly during the lifetime of the Space Station (and they are expected to) it may be necessary, in the course of this growth, to make the transition from one of these three sources to another. Issues of power growth therefore include the ability to make a transition from one source to another while supporting flight operations, to ensure technology readiness commensurate with growth in power needs, and to provide adequate scarring and other design accommodations for future alternative power systems. Since both photovoltaic and solar dynamic alternatives are under study for the IOC design, the Team felt most concerned about the nuclear power option. Do we adequately understand the design and technology implications of future transition to Space Station nuclear power to maintain this as a viable option for power growth?

The ability to increase the on-orbit presence of man is another area of generic growth. Without addressing the specific reasons for doing so, the Team recognized that a number of intrinsic benefits would result from more man-years per year on orbit. Increasing manned on-orbit activity will increase our ability to "think space" and produce intellectual benefits not possible with a Spartan, highly rotated crew. Enhancing our exposure to the space environment will enable us to more easily recognize its unique opportunities and hence tend to maximize the advancement possibilities. There is also the additional effect of "space" influence on ground-based colleagues that a widening Space Station experience would have, through both real-time communication and post-flight interactions. Naturally, such an underlying theme to increase man-years per year in space would generate a number of growth pressures on the Space Station: more and better crew facilities, better understanding of long-term space health effects, and improved life-support systems, to name just a few. The nature of crew and crew-time growth might be expected to be exponential in nature, at least during early to mid-term flight operations. Initially, very gradual growth in crew is expected, but as essential crew activities become routine (if they do), realization of opportunities for man-unique functions should grow, and with it the need for more man-years per year on board the Space Station.

The final subject of generic Manned Element growth considered by the Team was one of concern. The concern arises from the realization that simultaneous growth across a broad spectrum of Manned Element activities will lead to unacceptable operation conflicts, i.e., the "not-enough-hours-in-the-day syndrome." These conflicts are expected to be most severe between staging and servicing activities on the one hand, and microgravity and pointing activities on the other. The former operations, including satellite servicing, OMV/OTV staging and servicing, and Shuttle visitations, are expected by their nature to create a "dynamic" background to the Space Station environment. Conversely, microgravity and pointing (for Earth and space science) activities require a quiescent environment. As more of each type of activity is requested, conflicts will grow. A recurring question of growth during the Workshop, raised by this and other teams is: "Do you respond to such conflicts with in situ growth or should the conflicts be resolved with physically separable replication of facilities?" This issue will be addressed further in subsequent team reports.

The last question the Team considered regarding future Manned Element growth was: "What IOC design features being considered might inhibit growth?" The Team identified at least two such features: (1) the habitat/laboratory module concept, and (2) international facilities. Briefly, the Team felt that combining habitat and laboratory functions into individual modules could lead to inefficient growth. This concept tends to force simultaneous growth in habitation and Space Station usage. There is as yet no evidence to suggest that Station growth pressures will be so uniform. Separating laboratory and habitation facilities would permit a greater degree of flexibility in growth directions for the Manned Element. Regarding international cooperation, the approach of whole autonomous modules has been favored by some member nations. The alternative, of course, is to have specific functional responsibilities assigned to individual nations on the basis of interest and capability. In the case where whole modules are provided with autonomous capabilities, Space Station activities will be more partitioned and growth will become more difficult without attendant replication of basic functions. On the other hand, certain operational authorities are increased at the national level. With the view of maintaining maximum growth flexibility, a functional rather than facility-level distribution of responsibilities for international cooperation seemed preferable to the Team.

In summary, 11 different requirements and issues related to Manned Element growth were identified by the Team. Each of these is a candidate for future study to more specifically define the associated growth, necessary scarring, expected or possible time phasing, and requisite enabling technologies.

4.1.2 Team B: Platforms

Team B addressed the future uses of co-orbiting, polar, and geosynchronous platforms. User disciplines to be considered included Earth observations, astronomy, communications, plasma physics, materials processing, and basic physics and chemistry.

The Team grouped these disciplines into three classes for the purpose of discussion: (1) commercial (including materials processing); (2) applications (including observations, communications, and NOAA activities); and (3) science (including astronomy, plasma physics, solar and planetary activities, and terrestrial remote sensing). Platform growth in each of these three categories was the focus of the Team's deliberations.

Commercial users are expected to have a major influence on the evolution of co-orbiting platforms. The basis for this conclusion is found in the following user scenario proposed by the Team for growth in commercial activities. The current Space Station IOC data base at IOC and beyond envisions commercial buildup occurring at the Station core with attached modules or platforms. However, an evolutionary movement is likely when commercial viability, process development, and proof-of-concept advances occur. Commercial users may choose to utilize co-orbiting platforms because of heavy power needs and the requirement for continuous microgravity operations. Under this scenario, the Space Station core would continue to support commercial research and technology at the IOC level and beyond, but when production/manufacturing is ready, the activity would move to a co-orbiting platform. Given these conditions, the following growth issues are expected to impact the Space Station infrastructure:

1. Man-tended harvesting or recharge activities will occur for a spectrum of short time periods ranging from hours to weeks.

2. Servicing may be performed in situ or, alternatively, upon return to the Manned Element.

3. Co-orbiting platforms with large-area solar arrays will require active stationkeeping control (drag and gradient force compensation).

4. Closed-loop control systems must maintain the microgravity environment.

5. High transportation demands on OMV/STS will result from materials production throughput requirements.

6. Large and continuous (day and night) power requirements will exist, ranging from 25 to 40 kw.

7. The platform will probably need to be dedicated to the materials processing activities due to:

   - the need for a sustained microgravity environment; and
   - the possibility of vented contaminants.

Commercial activities in the form of orbital mapping and observations of land masses and the oceans were also expected to impact polar platform growth. These impacts were addressed by the Team in their consideration of the applications users.

The evolution scenario for applications users posed by the Team was initially similar to the commercial user situation, but differed in the later stages of growth. Initial platform activities of the applications users should include: (1) movement of traditional payloads and instruments from free-flyers to polar platforms; and (2) flight research and demonstration tests of new instruments on co-orbiting platforms or the Manned Element. As applications activities evolve, movement of instruments to the polar platforms will increase. This process will be observed as the evolution of a large complex polar platform payload, which changes and adds instruments as it progresses. With the growth in instruments and associated observing objectives will come the need for multiple platforms in different orbits, affording a variety of local crossing times and altitudes from which to conduct the requisite observations. Several growth impacts which polar platform planners should anticipate from such a scenario include:

- Increased data management capability:
  - more on-board storage, processing, and compression;
  - higher data rates; and
  - possible direct broadcasting.
- Enlarged coordinated instrument complements:
  - emphasis on longer life capability;
  - greater launch and servicing frequencies; and
  - increased platform resource capacity (e.g., power, space, control, etc.).

- Continuous operations (especially for commercial applications):

  - requirement for time-critical in situ servicing; and
  - investment in redundant instruments and platforms.

Geosynchronous platforms are, with the exception of communications, yet to be exploited by the applications disciplines. The Team felt, however, that this could be a significant area of platform evolution. The potential for real-time, continuous, and interactive, multispectral observations from geosynchronous orbit should strongly motivate the applications community once platform capabilities become apparent. Capabilities especially significant for geoplatforms will include large payload complements (perhaps preassembled at the Manned Element), low-gravity transfer capability to GEO (for larger space-deployed structures, e.g., antennas), and automated in situ servicing.

Evolution of platform use by the science community was felt by the Team to most directly impact the co-orbiting and geosynchronous platform elements of the Space Station. Nonetheless, the growing needs of the science users should reflect patterns already outlined in the evolution scenarios of the commercial and applications users. Platform usage for science is expected to evolve in orbit through the buildup of instrument complements into payloads operating in both independent and coordinate modes. Several co-orbiting platforms dedicated to science are expected by the Team as a result of this evolutionary process. Coordinated observation using interferometric telescopes is just one example of a multi-platform operation. Payloads will also include large orbit-assembled instruments. All of these science activities suggest a high level of servicing, repair, and on-orbit assembly. Given such evolved capabilities, the Team suggested that it may be possible to use co-orbiting platforms as staging nodes for planetary missions.

As with applications, the Team felt that geosynchronous platforms represent an unrealized opportunity for science. Large science payloads to GEO would be possible, using other Space Station infrastructure elements for assembly and staging. The science benefits of geoplatforms derive from real-time, continuous, interactive observations conducted with operational simplicity. The obstacles which confront science evolution to geoplatforms include transportation, advanced remote control and communications, and high level geoservicing. These are not unlike difficulties facing other potential geoplatform users. Hence, addressing these issues as part of the ongoing development of the Space Station infrastructure should attract a number of new users to geoplatforms.

In summary, Team B considered potential platform growth for three categories of users. The areas and relative levels of potential usage are apparent in the following matrix:

User Categories	**Platforms**		
	Co-Orbiting	**Polar**	**Geosynchronous**
Commercial Users	high	medium	---
Applications Users*	low	high	medium
Science Users	medium	---	medium

* Note that the Team included Communications with Applications Users in its discussion.

While all these applications won't be realized immediately, the growth potential of platforms as part of the Space Station infrastructure is clearly evident. The rate of growth will depend not only upon user foresight and economics, but also on the ability of platform development to meet the growing requirements of this broad spectrum of users.

4.1.3 Team C: Assembly, Servicing, and Staging

Team C addressed future assembly, servicing, and staging activities on the Manned Element. Included in their discussions were the servicing of platforms and free-flyers, the assembly of large structures for Earth observations, communications, and astronomy, and staging requirements for lunar and planetary missions.

The Team's discussion focused initially on formulating a broad definition of servicing (which included assembly and staging) and establishing certain basic precepts for Space Station servicing. This was followed by the identification of user servicing needs and the determination of the degree to which those needs should be met with IOC-level servicing. Evolutionary servicing scenarios were then considered; during this discussion the concept of infrastructure branching emerged. It became apparent that branching (or the lack of it) would directly impact the type of evolutionary changes imposed on servicing. Although there wasn't sufficient time for the Team to develop these relationships, several functions/technologies were identified which would enhance the ability of servicing to meet the needs of an evolving Space Station infrastructure. The Team also raised a Space Shuttle staging issue relative to Space Station support. These findings are briefly described in the paragraphs which follow.

The term "servicing" is used here in a very broad sense and includes several activities which might normally be thought of as being part of other areas of activity. Team C decided to include five functional areas within the definition of servicing, which are:

1. Activation (assembly, checkout, staging, and positioning);
2. Maintenance (resupply, reboost, and harvesting);
3. Upgrades (greater efficiency, lower cost, and greater capacity);
4. Deactivation (offload payloads, temporary shutdown, and orbit removal); and
5. Repair (reestablishment of partial/full capability).

Several servicing precepts were agreed upon by the Team as guidelines for subsequent discussion. Servicing should be viewed first and foremost as an economic issue, i.e., it is not for everyone. Nonetheless, the demand for servicing is perceived to be large, given the existence of a Space Station infrastructure. Servicing, as defined, must exist at IOC, albeit in a limited sense. Subsequent servicing evolution will be affected both by the Space Station's ability to service and by the user's ability to be serviced.

Potential customers for servicing activities and the types of service they are likely to require are summarized in the matrix below.

Users	Activation	Maintenance	Upgrades	Deactivation	Repair
Deep Space Science	X	X	X	X	X
Earth Applications	X	X	X	X	X
Materials Processing	X	X	X	X	X
Life Science	X	X	X	X	X
Technology Development	X	?	?	X	X
Deep Space Missions	X			(X)	
Space Station Infrastructure	X	X	X	X	X

Most users will need servicing of all types. Technology development users may require more limited servicing than most other users, since their payloads are more experimental in nature, and their missions are of shorter duration. Hence, such activities as maintenance and upgrading are less likely to occur. Payloads for deep space missions are not accessible to the Space Station after launch (excepting sample return missions, which also have a deactivation need) and therefore most of the servicing categories are not applicable for these missions. Not to be overlooked are the servicing needs of the Space Station itself. It is readily apparent that all five types of servicing will be required in the assembly and operation of the infrastructure.

Each of the types of servicing (activation, maintenance, upgrade, deactivation, and repair) will exist at IOC to a limited degree. As a minimum, planned IOC servicing must include the assembly of the Space Station itself, as well as provisions for payload setups and upper stage mating. Maintenance in the form of refueling, process harvesting, and resupply should be available, with the possibility for component replacement also considered. Some users may also be configured for early upgrading.

The current transportation data base indicates that more than half of the IOC servicing requirements will exist on the Manned Element. The remaining requirements involve bringing the servicing function to the user -- either in polar orbit, in a co-orbital location, or in a geosynchronous orbit. For these users, the ability to service is not so clear-cut. Many of these orbits are incompatible with servicing by the Station or Station-based OMVs. Even orbits at the Station's inclination have limited opportunities for access, due to nodal regression. Polar platforms will have to be serviced by the STS, with or without the help of an OMV. Free-flyers which opt for servicing will have to accommodate this requirement in their design at an additional cost estimated to be ten percent of the base cost.

Hence, the decision to service will be based on economic trade-offs, determined on a case-by-case basis. At IOC, Space Station servicing will be limited to those capabilities considered essential or strongly enhancing to users. As these services become routine elements of infrastructure operations, more and more user payloads will seek their benefits by designing to be serviced. At the same time, additional servicing capabilities will be added where needs are greatest. This process of expanding capabilities to meet economically justified needs is expected to characterize the evolution of Space Station servicing.

In a more generic sense, this form of evolution was recognized by the Team as progressive growth, which proceeds at a deliberate but more or less steady rate. But the Team also realized, at this point in its discussions, that there might also be stepwise growth of additional units and associated capabilities defined as "branching." Progressive growth has been recognized as a desirable attribute of the Space Station design from the beginning, including the idea of scarring the IOC design to enhance such growth. Branching, while not identified as such, has also existed for some time and is most easily recognized in the form of additional platforms being added to the Space Station infrastructure after IOC.

Branching, however, may also be important for the Manned Element, and this is a relatively new consideration. An example of branching the Manned Element would be the construction of a second manned (or man-tended) station to provide staging and transportation services rather than scarring and adding the OTV to the IOC Manned Element. The relationship of this type of branching to progressive growth (unit expansion) and the events which trigger branching decisions is illustrated in Figure 4. The key point to note is that, given a design philosophy which embraces progressive growth (as does Space Station), a barrier will eventually be reached beyond which the system design will not permit further expansion unless a fundamental change takes place. Barring a major technology breakthrough, the figure illustrates two types of branching which permit resumption of progressive growth. The first type of branching is that of replication, which resolves capacity barriers through sheer duplication; it is a "capacity" response. The second (and perhaps more probable) type of branching responds to conflicts which create barriers of diminishing returns and is a "functional" response. This branching divides responsibilities, reducing conflicts and simplifying infrastructure units which can then resume expansion in a more focused manner.

A key concern in the application of branching is that of timing. It may be difficult to forecast a branch point with sufficient lead time to avoid investments which become lost once the branching occurs. On the other hand, premature branching can lead to unnecessary and costly proliferation of infrastructure elements. Ideally, growth barriers are recognized well in advance of their occurrence, permitting the continued pre-branch expansion to develop in such a way that the initial unit maintains a high degree of utility after the branching occurs. This requires advanced planning, continued assessment of evolutionary pressure, and readiness investments in anticipation of identified potential branching.

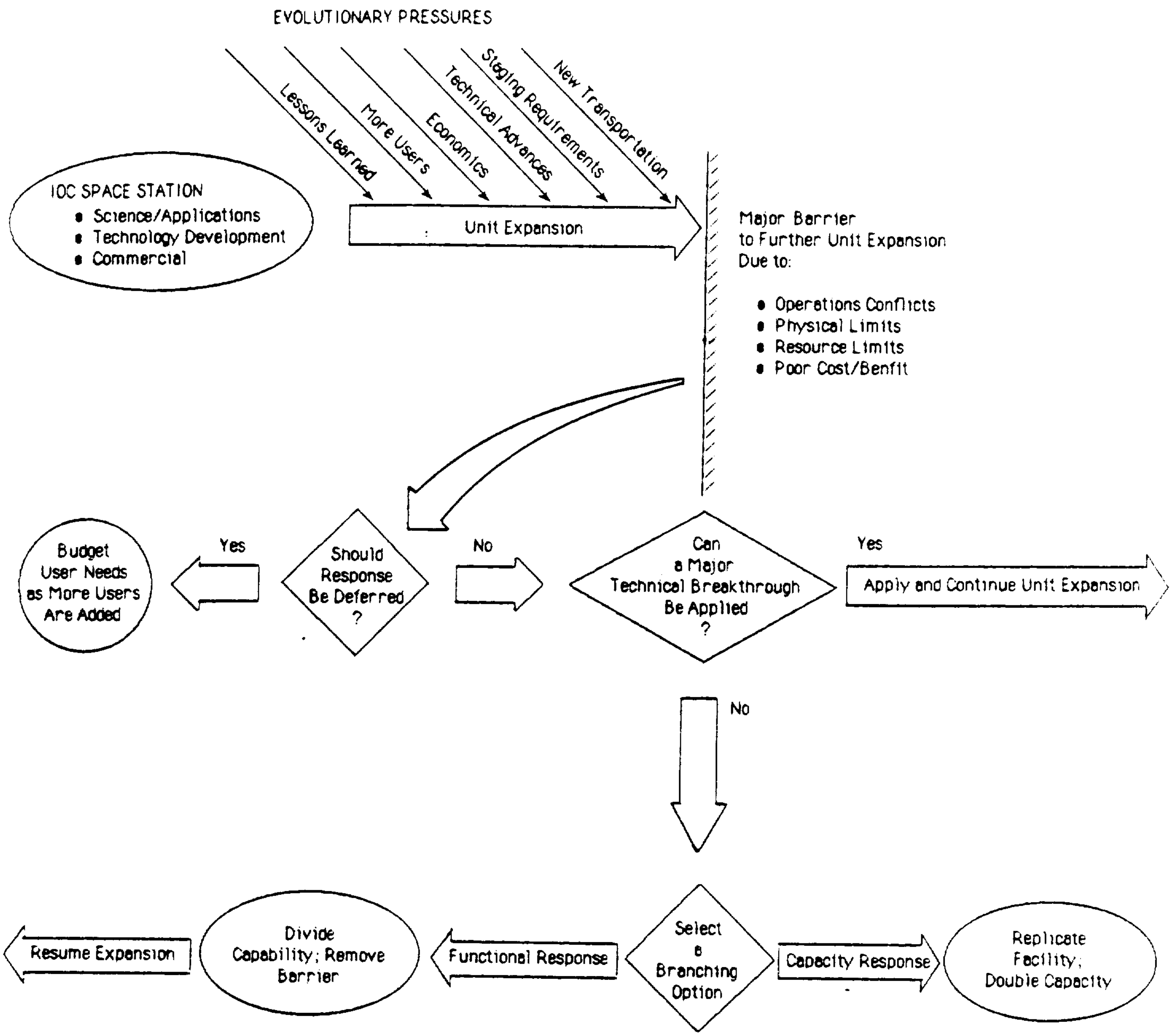


Figure 4. Space Station Evolutionary Process

As is so obviously apparent from the histories of evolving phenomena (e.g., life, nations, infrastructures, corporations, etc.), growth occurs progressively in one or more directions, occasioned by branch points which divide a direction into two directions. A truly evolving Space Station will also demonstrate this characteristic.

Several examples were suggested by team members to illustrate when and why branching might take place. Among these examples were the following:

Impetus	Branching Rationale
AM and PM Polar Platforms	Platform duplication necessary to meet requirements which have incompatible orbital constraints
New Commercial Market	Co-orbiting platform duplication to provide adequate resources to meet rapidly growing user requirements
Space-Based OTVs	Manned Element branching as a functional response (propellant form and staging) requirement
Manned Mars Program	Creation of new functional element to assemble and check out manned Mars hardware in Earth orbit (this element might even become part of the manned mission itself).

Other examples undoubtedly exist. The point to be made is that the IOC Space Station will probably fall short of meeting the wide range of requirements envisioned over its lifetime. A key criterion of effective Space Station evolution is its ability to branch its capabilities as a means of growth, and to be able to do so in a cost-effective manner. Timing is therefore as important to growth as is the nature of the added capability derived from branching.

Returning to the specific issue of servicing in the Space Station era, the Team had several technology observations to offer. Servicing in space may often require automation and robotics as key enabling technologies. The hostile environment, coupled with the need for safety and the effective use of people, indicates a strong requirement to utilize as much automated assistance as possible. In some cases (such as long-duration continuous activities or servicing at long distances from the home base), automation and robotics may be the only reasonably feasible ways to accomplish the servicing tasks. A major technology requirement inherent to the expanded use of automation and robotics for servicing will be sophisticated expert systems able to handle not only routine events but also a wide range of problems. It is anticipated that the assembly of large structures will also be a key capability in the evolving Space Station infrastructure, and it is viewed as a major servicing function.

The role of servicing will change as the infrastructure and uses of the Space Station change. Utilization of nuclear power, for example, will require considerably different servicing support than will a Space Station powered by solar dynamics. Such changing roles will continue to dictate new technology development requirements.

Finally, the Team raised an interesting issue relative to staging at the Manned Element. Assuming that the Space Shuttle represents a limited launch capacity (before the development of a Heavy Lift Launch Vehicle or other alternative launch systems) in the Space Station era, would it be feasible to stage Shuttle payloads from the Manned Element, thereby permitting each Shuttle to launch with a full cargo bay? Certainly, some payloads would be at a disadvantage if their orbits were significantly different from those of the Space Station. The trade-off of interest, however, is whether a net advantage or disadvantage is experienced by mandating the Manned Element as a staging node, which enables the Shuttle to fly full all the time. Secondary concerns involving payload management at the Space Station would also have to be addressed. While the Team had neither the time nor the expertise to resolve this issue during the Workshop, it did want to bring up the idea of maximizing Shuttle throughput for subsequent assessment and resolution.

4.2 Session 2: Evolution Scenarios

Using the growth requirement results of the first session, the theme of the second session was to develop evolution scenarios driven by various growth emphases. Teams were formed to examine the evolution of the Space Station infrastructure resulting from three different directions of user growth, namely:

1. Research and technology growth;
2. Commercial growth; and
3. Growth caused by a major new space initiative.

In each case, the scope of the team's assessments began with a refined definition of anticipated growth; i.e., which broadening applications or new missions would specifically characterize the area of growth being emphasized. The next step of team evaluation was to identify both the anticipated new requirements and the possible infrastructure growth options needed to meet the anticipated growth. This was followed by an assessment of impacts on the IOC design, suggested IOC scarring for growth, and the identification of new technologies most likely to enhance the growth process. Finally, each team identified trade studies which should be performed to improve our understanding of Space Station growth potential and associated activities/design decisions which would enhance such growth.

4.2.1 Team D: Research and Technology Growth

The Team was charged with establishing an evolutionary Space Station scenario with a research and technology emphasis. Accordingly, it was assumed that this meant a continued increase in science, technology, and commercial experimentation facilities for the IOC Space Station to a level capable of meeting all such users in the data base. Included in this expansion would be the assembly of large structures at the Manned Element, transportation to GEO and other higher energy orbits from the Station, and servicing at GEO. The Team did not attempt to break growth down between specific areas of research and technology growth, but chose rather to address such growth as a single area of consideration.

Anticipated Requirements. The additional requirements identified by the Team to meet emphasized research and technology growth are summarized in Table 6 by infrastructure element. The results of other teams were used as key inputs to establish these needed research and technology areas. Similar

Table 6

ANTICIPATED SPACE STATION REQUIREMENTS WITH RESEARCH AND TECHNOLOGY GROWTH

Infrastructure Element	Requirements
• Manned Element	- Module to House Laboratory for Hazardous Research - Early Orbital Transfer Vehicle - Assembly of Large GEO Instruments/Structures - Increased Power - Increased Orbital Servicing - Tether User Support (down and up)
• Co-Orbiting Platforms	- Multiple Platforms - Nano-g ($<10^{-8}$) Research Environment - Manned Element Precision Stationkeeping - Increased Power (level TBD) - Enhanced Ability to be Serviced
• Polar Platforms	- Multiple Platforms - Increased Data Capacity - Increased Power - Enhanced Ability to be Serviced
• GEO Platforms	- Accommodation of Large (size/mass) Instruments
• Transportation Systems	- Maximized STS Payloads - Early Orbital Transportation Node - Low-g Orbital Transfer Vehicle

requirements affecting more than one element are listed for each affected element. Note that the Space Station infrastructure is treated here as composed of five elements, namely: (1) the Manned Element; (2) co-orbiting platforms; (3) polar platforms; (4) GEO platforms; and (5) transportation systems, including the STS and various orbital stages.

New requirements for the Manned Element begin with a module housing a laboratory for hazardous research. This module, automated and safely isolated from other modules, would be used for conducting research of a hazardous nature. Subjects of interest include fire suppression tests, gas detonation experiments, "waste" processing, and research with biological and toxic substances. Another new requirement would be facilities for tether users, which have the ability to extend tethers both down and up. For a growing community of GEO users, the requirement to assemble large instruments and structures at the Manned Element could be added. To support any GEO activity at all, the Manned Element will be, first and foremost, a staging node. To fulfill this role as soon as possible, an early requirement to accommodate expendable orbital stages (e.g., PAM, Centaur, TOS, etc.) is anticipated. For example, a large payload for GEO might be assembled at the Station with a Centaur brought up later for mating, checkout, and deployment. Later on, this requirement would be superseded by a space-based Orbital Transfer Vehicle (OTV) permanently based at the Manned Element. All of these requirements create the need for additional power to run the laboratory for hazardous research and the tethers, to assemble, check out, and mate large GEO payloads and orbital stages, and to maintain stored cryogenic propellants for an OTV. Similarly, these, and other requirements discussed below, will increase the requirement for orbital services at the Manned Element. Already mentioned were the servicing activities of assembly, checkout, and stage mating. Other services needed will include platform tending, disposal of hazardous and/or toxic materials, and repairs/maintenance of space-based OTVs.

Assuming that a modular approach to co-orbiting is adopted, a number of additional platforms will be required. These will be used for a number of basic physics experiments, as well as materials and fluids research, requiring maintained micro- to nano-g-level environments. Several of these platforms may also support interferometer instruments and will therefore also require precision stationkeeping with the Manned Element. (It should be noted that microgravity and precision stationkeeping may not be platform-compatible requirements, since stationkeeping may require matching the drag effects of the Manned Element.) The possible requirement for increased platform power will depend upon the yet-to-be-defined payloads and experiments to be accommodated, e.g., manufacturing moved off the Manned Element to platforms. Finally, an improved ability to be serviced will be required at each platform. While certain free-flyers, such as the Hubble Space Telescope, will probably be serviced at the Manned Element, most platform servicing will be in situ. This will require a "smart" front end for the OMV and service design considerations for the platforms themselves.

Polar research and technology needs by the year 2000 are expected to require up to six polar platforms spread over a range of local times (nodal positions). These platforms are expected to be required to provide up to 20 kw each and, as an aggregate, to have a total average data capacity of 500 to 600 Mbps. As with the co-orbiting platforms, they will have to be designed for servicing, which is expected to occur at two-year intervals to minimize disruption of operations, and would be accomplished by the STS/OMV.

A substantial need is anticipated for very large (both in size and mass) instruments at GEO for both Earth observations (primarily climate-related) and astronomy. It is not yet known whether these will be free-flyers or become part of a GEO platform payload. What is expected is their required assembly at the Manned Element and their "soft-boost" ($\approx$0.1 g thrust) to GEO.

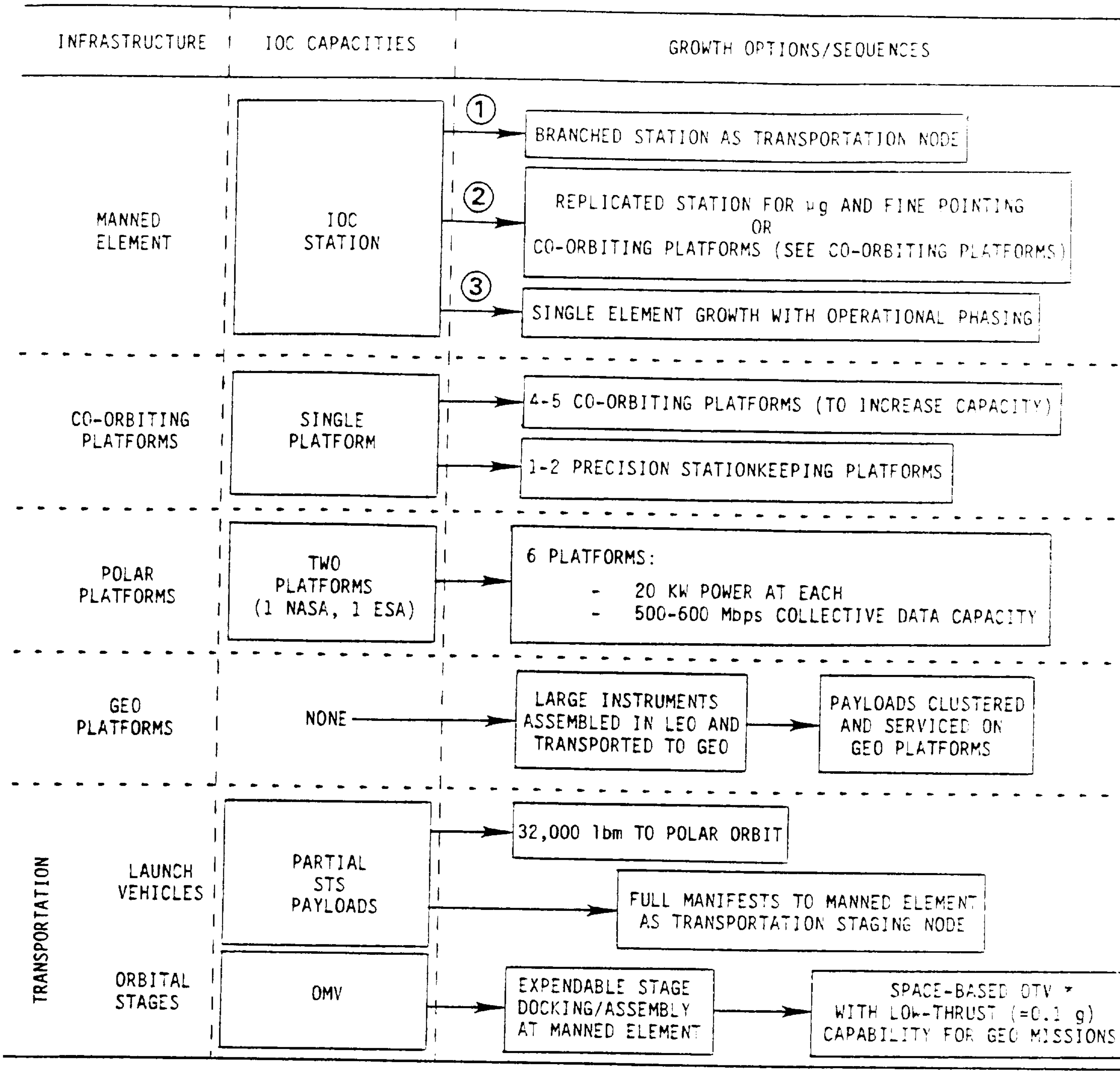
Finally, in Table 6, the additional transportation requirements which are anticipated to support research and technology growth are given. Foremost is the need to maximize STS payloads. By using elements of the Space Station as staging nodes, fully manifested payloads could be flown on every Shuttle launch, providing the maximum throughput to orbit with what will most certainly be an oversubscribed four-Orbiter fleet. In polar orbit, such a staging node might be a man-tended platform which is functionally equivalent to an orbital "line-shack." Payloads delivered to this platform could be subsequently distributed to the various operational polar platforms by a space-based OMV as the "line-shack" drifted under each one. At the Manned Element, GEO payloads could be mated to existing orbital stages (e.g., PAM and Centaur) if staging requirements can be met, again greatly increasing the flexibility and size of Orbiter payloads. Each of these examples increases the average manifested payload and decreases the number of Shuttle launches required for a given payload set. The final transportation requirement expected by the Team was a lower-thrust (≈0.1 g) stage for maneuvering large, Space Station-assembled, and fragile instruments from LEO to GEO. Such a stage would probably be specific to this particular mission.

Infrastructure Growth Options. The requirements of a growing Space Station Research and Technology Program would trigger a number of evolutionary steps in the infrastructure. The specific and optional growth sequences identified by the Team are summarized by infrastructure element in Figure 5.

To meet the Research and Technology requirements it is clear that the Manned Element must grow/evolve to provide increased resources commensurate with the data base statement of need. Three options for growth were identified by the Team. These are:

Option 1 - Branching in the mid-1990s to accommodate the OTV transportation function. In this case, the IOC Station resources grow to accommodate research needs. Transportation, servicing, and assembly/construction are accommodated on a new Manned Element. This division of requirements greatly reduces the micro-g disturbances on the IOC Station by reduction of STS flights, reduction of MRMS use, reduction of EVAs, elimination of large mass changes (and c.g. shifts), and elimination of OMV and OTV berthings. The transportation staging functions of the new Space Station would become a focus for automation and robotics technology development.

Option 2 - Movement of micro-g research and fine pointing activities to co-orbiting platforms or a replicated Space Station, again in the mid-1990s. In this case, the IOC Station resources grow to meet all R&T needs until platform or Station replication. At that point the IOC Space Station becomes a facility dedicated to servicing, transportation, and assembly and construction. Placement of micro-g research and fine pointing instruments (arcsec to sub-arcsec pointing) on platforms will eliminate all disturbances except for periodic servicing and orbital drag.



NOTES: (X) ≡ GROWTH OPTIONS

* A SPACE-BASED OTV ALSO IMPLIES MANNED ELEMENT GROWTH ACCOMMODATIONS INCLUDING PROPELLANT RESUPPLY FACILITIES

Figure 5. Infrastructure Evolution with Growth in Research and Technology Disciplines

Accommodation of micro-g research in this mode, however, will require significant advances in automation and robotics. If, on the other hand, these activities are placed on a replicated Station, some degree of disturbance will continue to exist, including crew motion, EVA/MRMS activities associated with instrument placement and servicing, and STS logistics flights.

Option 3 - Continuation of all R&T activities at an evolving IOC Space Station. In this case, the IOC Space Station grows and evolves to meet the needs dictated by the data base. Time phasing of mutually interfering activities will become more and more critical. Frequent STS logistic flights will interfere with micro-g research and fine pointing. OMV and OTV berthings and servicing will also conflict with micro-g research and fine pointing. Tether activities (down and up) will not only disrupt micro-g research, but will also obstruct instrument field of view and inhibit proximity operations. Finally, as the number of activities increases, competition for available resources will also mandate time phasing.

The number of 28.5-degree platforms is likely to increase (to ≈5-7) if a modular approach to platform subsystems is adopted. Some platforms, such as the Hubble Space Telescope, will require servicing at the Manned Element. In general, however, it may be desirable to perform most servicing *in situ* (at the platform). This will require a "smart" front end for the OMV. Several of these platforms may also have to meet precise stationkeeping requirements with each other or the Manned Element.

Research and Technology emphasis is also expected to increase the number of polar platforms by the year 2000 to approximately six, located at different local times and with a power capability of 20 kw each. The total average data rate from these platforms will be 500 to 600 Mbps. Servicing, at about two-year intervals, will be accomplished via STS/OMV at the platform (rather than at the STS) to minimize disruption of operations. Initial delivery of the platforms to orbit may require a Western Test Range STS payload capability of 32,000 lbm.

No GEO activity is included in the IOC Space Station infrastructure. However, if available upper stages can be docked at the Manned Element, an early R&T growth option would be the assembly of GEO instruments at the Space Station. These would then be mated to the waiting stages, checked out, and launched to GEO. As this activity matures, larger instruments would be assembled at the Space Station, requiring more servicing capability, and because of their fragility, a new "soft-thrust" transfer stage. If this activity is sustained, it is expected that GEO instruments would eventually be clustered on platforms sharing common resources and simplifying on-orbit servicing requirements.

Transportation requirements associated with R&T-motivated infrastructure growth will necessitate STS and orbital improvements as well. These are summarized in Figure 5 and have already been addressed above with respect to individual element growth options and sequences.

IOC Design Impacts and Scarring. A number of issues raised in the discussion of R&T requirements and related infrastructure evolution have an impact on the IOC design. For the Manned Element, design questions arise regarding the location and safe operation of a Laboratory for Hazardous Research. The accommodation and operation of tethers extending both down and up is another design consideration. Orbital stage management is an issue which not only affects IOC design but is ever-present during evolution. If IOC design can accommodate expendable stages, new GEO R&T activities can commence early in the Space Station era. Eventually this approach will be replaced with a space-based OTV, adding new requirements for space maintenance and substantial propellant management ($\approx$100,000 lbm). The ability to perform extensive servicing at the Manned Element will be a major key to R&T growth. Servicing will be required to set up platforms, to assemble payloads, to mate and maintain stages, and to perform resident housekeeping functions. An IOC design with adequate servicing considerations will substantially enhance subsequent growth potential. Likewise, R&T growth emphasis suggests a strong crew presence with subsequent growth in crew size. Hence, IOC human factors design will need to carefully address the diverse subjects of life-support system closure, improved EVA systems, and special transport/rescue requirements. With the anticipated high degree of activity at the Manned Element, adequate design consideration will have to be given to resource growth, specifically power (up to 500 kw) and to logistics management. If the Space Station is not only supporting a host of diverse <u>in situ</u> activities, but also becomes a staging base for five to seven co-orbiting platforms, GEO payloads, and orbital stages, logistics management and its attendant design impacts must be addressed before IOC.

Scarring of the Manned Element will emerge from design impact studies, in anticipation of growth. Specific scarring candidates include interfaces for the Laboratory for Hazardous Research and the tethers, docking ports for both space-based and expendable orbital stages, properly sized and outfitted servicing bays, identification of assembly areas for large structures with proper attach points, external aids for EVA activities, warehousing areas to accommodate logistics growth, and design accommodations for four-to five-fold power growth.

One additional important issue impacting both the IOC design and associated scarring is branching. The Team defined three different options for accommodating conflicting R&T growth requirements on the Manned Element: (1) branch transportation growth to a new station; (2) move micro-g and fine pointing activities to platforms or a replicated station; and (3) use activity time-phasing to cope with the interference. Trade studies (defined below) need to be performed to ascertain the probable direction of growth. The level of IOC design impacts and scarring is highly dependent upon which growth mode is adopted by the Program.

Co-orbiting (28.5°) platform design is also impacted by an R&T growth emphasis. Modularizing platform subsystem design would facilitate growth in the number of co-orbiting platforms supporting Space Station R&T activities. Additional IOC platform design considerations include in situ serviceability, provision for power growth, and enhanced stationkeeping ability. Scarring should focus on enhancing modularity, serviceability, and power growth.

Polar platforms share many design impacts with co-orbiting platforms. In situ serviceability and power growth (to 20 kw) are most important. Areas of special concern to polar platforms include increased data capacity (up to 600 Mbps for six platforms) and launch performance constraints (32,000 lbm maximum with Shuttle). Scarring should address modularity aids for growth, in situ serviceability, and accommodations for power and data rate growth, independent of any direct association with specific mission sets.

Table 7

TECHNOLOGY NEEDS STIMULATED BY RESEARCH & TECHNOLOGY GROWTH REQUIREMENTS

Requirement	New Technologies
Orbital Transportation	Space-based OTVs will require technology development for cryogenic fuel handling, storage, and transfer, as well as automated servicing and checkout.
Information Management	Increased data collection rates require data compression and/or storage technology development to avoid significant data rate increases; transmission and handling capabilities (both TDRSS and ground stations) will also need to be improved.
Power	Growth to 500 kw of Manned Element power will require at least solar dynamic technology (if not already available at IOC).
Crew Size	Anticipated increased crew size will motivate increased closure of life-support systems and may require special "people carriers" for crew rotation and/or rescue.
EVA	Large amounts of EVA associated with R&T activities will require the development of improved suits, tools, techniques, and aids.
Operations	Increased use of automation and robotics technologies is key to increased productivity and reduced operations costs across all Space Station functions.
In Situ Servicing	Automation, Robotics, and Artificial Intelligence technologies will need to be applied to the development of a "smart" front end for the OMV.

R&T-Relevant New Technologies. In its discussion of Research and Technology growth emphasis a number of technologies were recognized by the Team as being important stimulants to such growth. Recognition of enabling and/or enhancing technologies is motivated by the new requirements imposed on the infrastructure by expansion of activities, in this case R&T activities. For each of seven important growth requirements defined by the Team an associated set of new technologies was identified. These are summarized in Table 7. It should be noted that this is by no means a complete set. Further useful technologies are expected to become evident in the conduct of important trade studies recommended by the Team in support of R&T growth.

Trade Studies. The Team identified six specific trade studies which were felt to be especially important to understanding the potential and direction of Space Station growth motivated by Research & Technology activities. These are as follows:

1. **Assessment of the impacts and benefits of the three options identified for Manned Element evolution.**

   How effective will time-phasing of requirements be in accommodating incompatible activities such as micro-g research and OTV operations (Option 3)? How long can this approach be applied before R&T growth becomes seriously impaired? To separate conflicting activities, should the Manned Element be replicated at some point, leaving the transportation node functions on the initial station (Option 2) or should transportation requirements be deferred until such time as a branched transport/service station can be developed (Option 1) ? What are the key parameters influencing these trades and how sensitive are trade study conclusions to their accuracy?

2. **Trade-offs of impacts and benefits of tether activities.**

   How significant are tether activities to R&T growth? What constraints are imposed by the presence of tethers on other R&T activities? Is the technology strong enough to support timely development of tether systems? What are the individual benefits/impacts of down and up tether systems? What are the important safety issues related to tethers?

3. Assessment of impacts/benefits of early introduction of the transportation node function by using existing upper stages (e.g., Centaur and PAM).

What data base user missions are enabled by the early establishment of the transportation node function at the Manned Element? What scars/modifications/additions are needed to perform this activity? How compatible are these adjustments with the subsequent introduction of a space-based OTV? What are the important safety issues related to solid- and liquid-fueled expendable stages? Is there sufficient marginal capacity in the STS Orbiter fleet to support such an idea?

4. Analysis of impacts/benefits of space-based OTV flight activity up to the rate of ten sorties per year by the late 1990s.

Does the R&T data base (GEO users especially) support this level of activity? Can the STS support the propellant and spare part logistics or is an additional launch system needed? If so, what? What are the Manned Element differences between a two flight/year and a ten flight/year OTV capability? At what point (if within the ten flights/year) do incompatibilities with other R&T activities (e.g., micro-g and fine pointing) drive incompatible functions apart through platform replication or Space Station branching? What are the key OTV safety issues? Do they change with increasing flight rate? If so, how?

5. Conduct of cost/benefit analyses of data compression/storage/transmission/direct broadcast to accommodate data handling needs.

What are the costs versus capacity trades for the various data handling alternatives to be addressed? How critical are new technologies to assumed achievement capacities? What are the weakest elements of each approach? How sensitive are cost and performance results to assumed parameters? Which approaches have intrinsic future growth potential? Which alternatives build most easily from IOC systems?

6. Assessment of impacts and benefits of *in situ* servicing.

Which elements of the Space Station infrastructure are candidates for *in situ* servicing? Rank each according to benefits, and according to impacts? What are key enabling technologies for in situ servicing? What are the differences (cost, capability, availability) between manned and unmanned in situ servicing? What R&T growth options require or are strongly enhanced by in situ servicing? Assuming either the Manned Element or the Shuttle is home base for in situ servicing equipment, what are the specific impacts on these systems? What operational changes must they accommodate with in situ servicing? Without it?

4.2.2 Team E: Commercial Growth

This team addressed the requirements and evolutionary patterns of the Space Station infrastructure resulting from an emphasis on commercial growth. It is assumed that the success of initial experimentation on the Space Station will lead to the substantial expansion of identified commercial activities - as predicted by the present Space Station user data base - and even greater commercial applications equivalent to "factories" in space. These possibilities include Earth observations, materials processing, satellite servicing, transportation, and others. Four areas of commercialization were chosen by the Team as themes for their discussions. These are: (1) manufacturing and transportation (M&T); (2) Earth and ocean observations (EOO); (3) commercial GEO communications (COMM); and (4) industrial services and operations (S/O). The Team addressed growth requirements and possible infrastructure evolution motivated by each of these areas of commercialization. Space Station design impacts, scars, technology requirements, and trade studies are subsequently presented below as an aggregate response to these commercial activities.

Anticipated Requirements. Requirements identified by the Team as a result of commercial growth are summarized in Table 8 by infrastructure element, broken down among the four areas of commercial growth emphasis, i.e., M&T, EOO, COMM, and S/O. Some requirements affect more than one element and hence appear several times in the table.

The Manned Element is expected to face growth requirements imposed by increases in both M&T and COMM activities. Beginning with Manufacturing and Transportation, increasing this activity beyond pilot IOC projects almost immediately calls for increased logistics management. Utility consumption

Table 8

ANTICIPATED SPACE STATION REQUIREMENTS WITH COMMERCIAL GROWTH

Infrastructure Element	Requirements	Growth Emphases			
		M&T	EOO	COMM	S/O
• Manned Element	- Increased Logistics Management	X		X	
	- Transportation Node Staging			X	
	- Increased Utilities	X			
	- Increased Operational Complexity	X			
	- Extended Crew Accommodations	X		X	
	- Contamination Control	X			
	- Large Structure Construction			X	
	- Branched Station	X			
• Co-Orbiting Platforms	- Increased Data Handling		X		
	- Increased Utilities	X			
	- More On-Orbit Fuel	X			
	- Increased Operational Complexity	X	X		
• Polar Platforms	- Increased Data Handling		X		
	- Increased Operational Complexity		X		
• GEO Platforms	- Increased Logistics Management			X	
	- Extended Crew Accommodations			X	
• Transportation Systems	- Increased Launch Capacity	X			
	- Increased Logistics Management	X		X	
	- Transportation Node Staging			X	
	- Extended Crew Accommodations			X	
	- Increased Operational Complexity		X		
	- Low-g Orbital Transfer Vehicle			X	
	- Logistics for Branched Station	X			
• All	- New Pricing Policies	X	X	X	X
	- Insurance/Liability Management	X	X	X	X
	- Other Policies (access, usage, etc.)	X	X	X	X

also will increase, as will operational complexity, as manufacturing and transportation compete for services and resources. As manufacturing grows, economically viable activities may move to dedicated, co-orbiting platforms. This may entail certain man-tended operations resulting in increased crew accommodations on the Manned Element. Increased manufacturing means new requirements for the control and disposal of contamination by-products. And ultimately, if manufacturing or transportation threatens to dominate Manned Element activity, the requirement for branching to a new station would have to be considered.

Vigorous growth in GEO communications (COMM) will impose significant new staging requirements on the Manned Element. Again, increased logistics management leads the list. Transportation staging at the Station is considered key to COMM growth. Initial basing of expendable upper stages, followed by space-based OTVs to be mated to COMM payloads for deployment to GEO is the preferred scenario. This implies extended crew accommodations in the near term and imposes them as a requirement in the longer term if the COMM activity grows to the level of man-tended GEO platforms using manned OTVs. Finally, as the activity matures, assembly of larger COMM payloads at the Manned Element is expected. Requirements for assembly, checkout, and deployment (stage-mating) all become part of the intensifying COMM activity.

Co-orbiting platforms will be most affected by M&T growth, and, to a lesser extent, by EOO activities. Manufacturing on co-orbiting platforms will increase utility (principally power and stationkeeping) demand with power levels as high as 50 kw expected. On-orbit fuel for platform stationkeeping and servicing (by OMV or manned EVA) will have to be increased. As the number of manufacturing platforms increases, so also will the complexity of operational requirements.

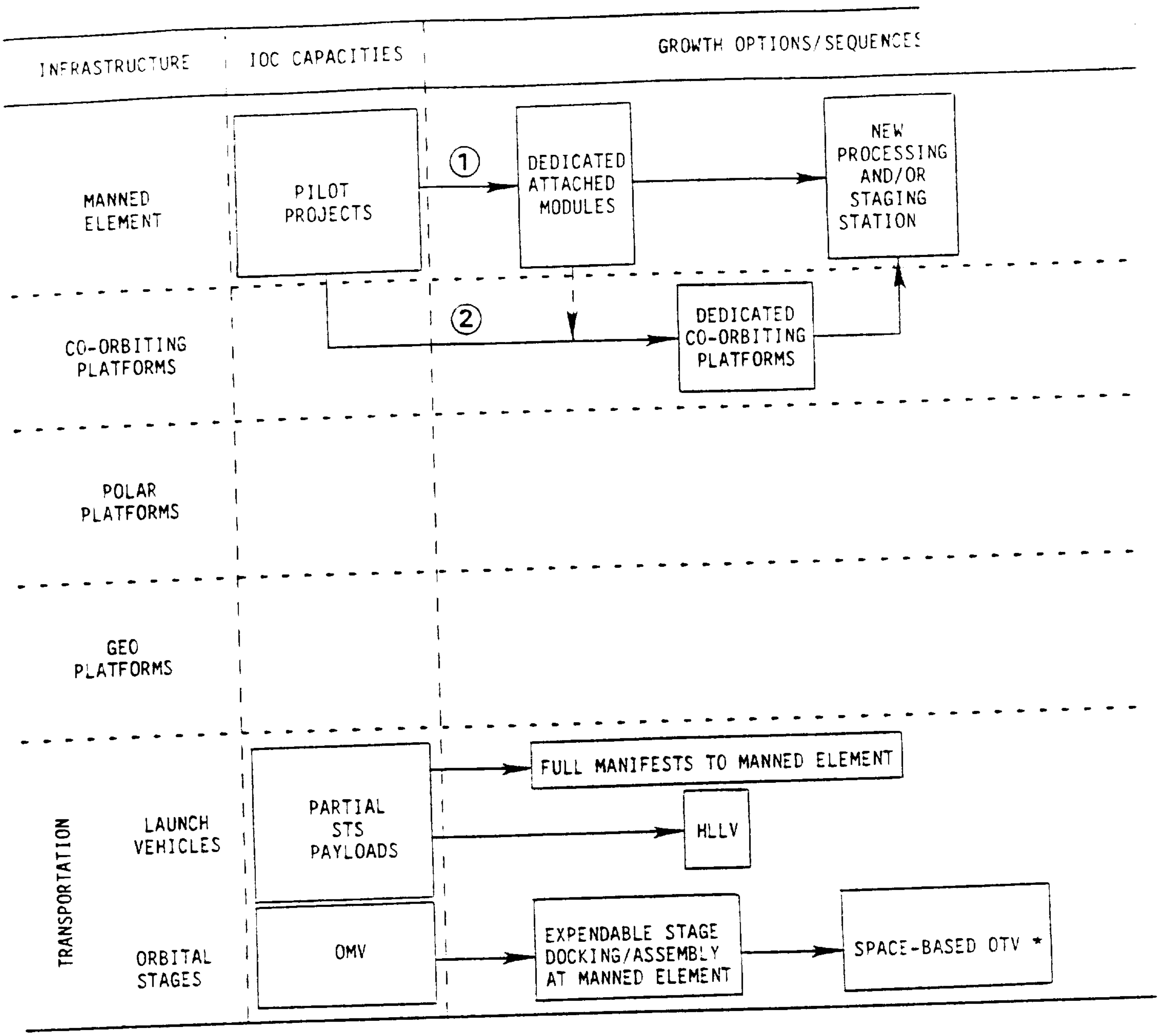
EOO activities, to a limited degree, will occur on co-orbiting platforms. Their requirements will be for more data handling, and, operating in conjunction with other platform activities, they will increase operational complexity. The primary impact of EOO growth, however, is expected to be on polar platforms. Again, increased production of data will lead to new handling and transmission requirements, attended by increased operational complexity of the platform payload.

The advent of GEO platforms resulting from vigorous COMM growth will impose at least two specific requirements. First will be the need to manage logistics at the platform related both to the COMM payloads themselves and to their associated servicing needs. Second, assuming man-tended operations, extended crew accommodations will have to be considered shared in some way between the visiting manned OTV and the platform itself.

Transportation Systems will see many of the same requirements imposed on them by M&T, EOO, and COMM growth as are expected for the various Space Station infrastructure elements. These include increased logistics management (e.g., Shuttle and orbital stage payload manifesting), transportation node stage in LEO, extended crew accommodations (e.g., the manned OTV), increased operational complexity (e.g., servicing polar platforms), and possibly added logistics support for a new "manufacturing" station. Transportation-specific growth requirements include an obvious increase in launch capacity to support evolutionary M&T growth, and lower-thrust orbital stage capability for the deployment of large, fragile COMM payloads to GEO platforms.

Finally, there are several new requirements anticipated for the Space Station Program which are particularly precipitated by commercial growth. These include economically motivating pricing policies, management of liability issues and associated insurance coverage, and a range of other policy issues (including partnership agreements, user access, usage priorities, and control authority, to mention a few). The growth in commercially provided services and operations (S/O), which has not imposed any other requirements to this point, is an activity which will impose many such requirements before it can be expected to grow.

Infrastructure Growth Options and Impacts. The imposed requirements of commercial growth would precipitate evolutionary steps in the Space Station infrastructure that would differ depending on the specific activity experiencing growth. For each of the four areas of activity considered by the Team



NOTES: (X) = GROWTH OPTIONS

* A SPACE-BASED OTV ALSO IMPLIES MANNED ELEMENT GROWTH ACCOMMODATIONS INCLUDING PROPELLANT RESUPPLY FACILITIES

Figure 6. Infrastructure Evolution with Commercial Growth Emphasis: Manufacturing and Transportation

(i.e., M&T, EOO, COMM, and S/O) a specific scenario of evolution was forecast. These scenarios and the resultant impacts on infrastructure elements are presented below for each growth activity.

Expected Space Station evolution motivated by growth in Manufacturing and Transportation (M&T) is depicted, for each infrastructure element, in Figure 6. Changes are seen for the Manned Element, possibly Co-Orbiting Platforms, and supporting Transportation. It was felt that the IOC Station would be used primarily for pilot manufacturing projects paralleled by similar activities on Earth, with balloons, and on the Shuttle Orbiters. As production capabilities mature and capacity requirements grow, two evolutionary options are foreseen. In the first option, dedicated attached modules which impact utility capacities are added to the IOC Station, i.e., substantial increases in power and thermal control are envisioned. The second option would utilize co-orbiting platforms for production, and might also employ them as payload mating bases using expendable orbital stages. Impacts for this scenario include increased operational complexity, more sorties to and from the Manned Element, and higher platform power requirements. Increased crew accommodation at the IOC Station for co-orbiter support should also be expected. A specific advantage of this platform option would be the long-term duration of a micro-g environment. As an alternative to choosing between these options, option one could be followed by option two, i.e., manufacturing could proceed from pilot projects to dedicated modules to co-orbiting platforms. If M&T growth continues into the longer term, either of these options could take one more evolutionary step to a dedicated M&T Station, possibly developed with support from the commercial sector. In this same time frame, lunar and asteroid resource mining would also be considered commercially viable. Impacts of a branched Station would include added logistics complexity, especially if the IOC Station is used as a construction base for the commercial Station. And more logistics means more launch services.

Transportation growth would be required for both launch systems and orbital vehicles. STS payload manifesting would have to be maximized in the near term, substantially augmented by a Heavy Lift Launch Vehicle (HLLV) or an equivalent before the Manned Element could function as a significant trans-

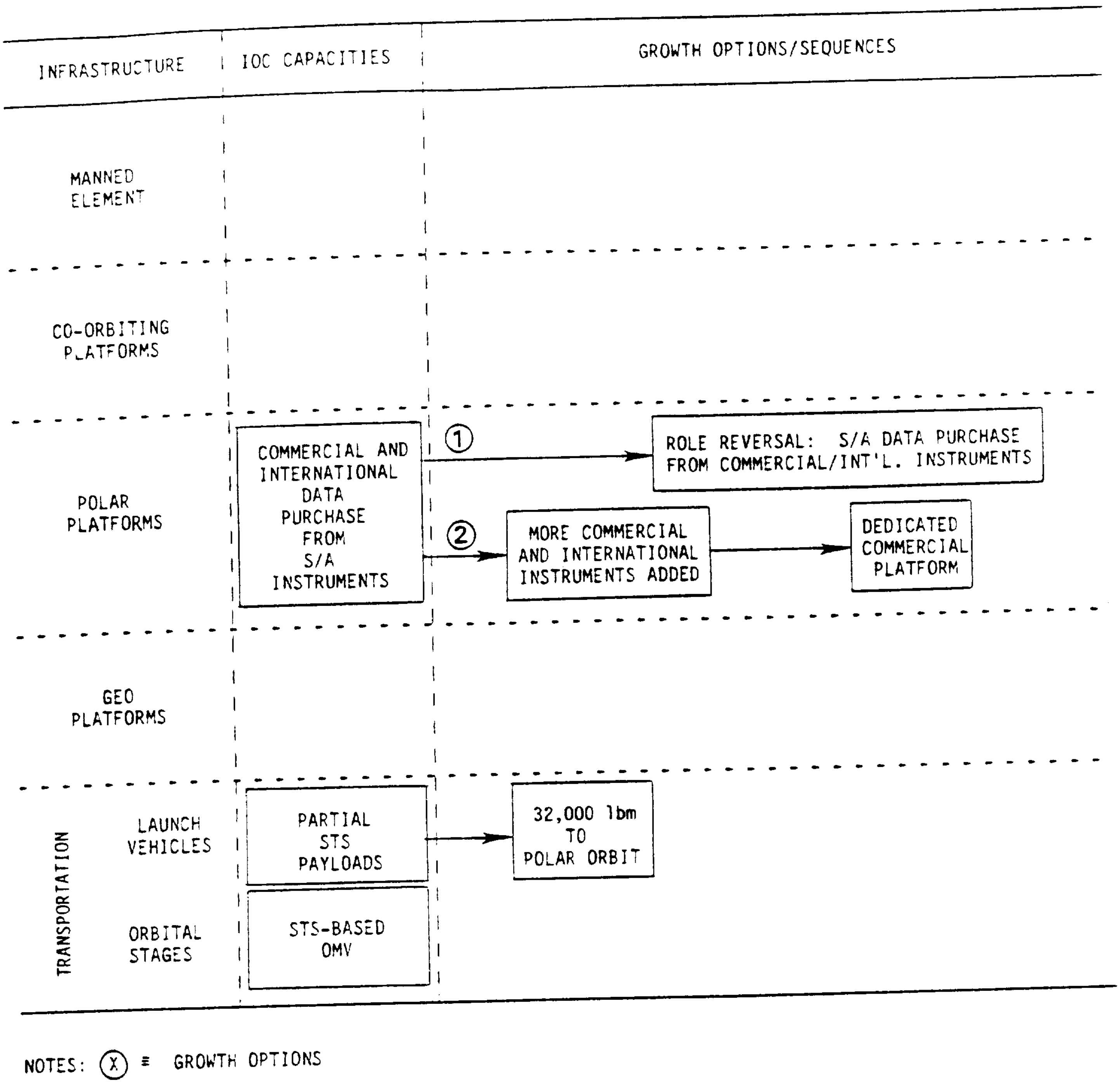
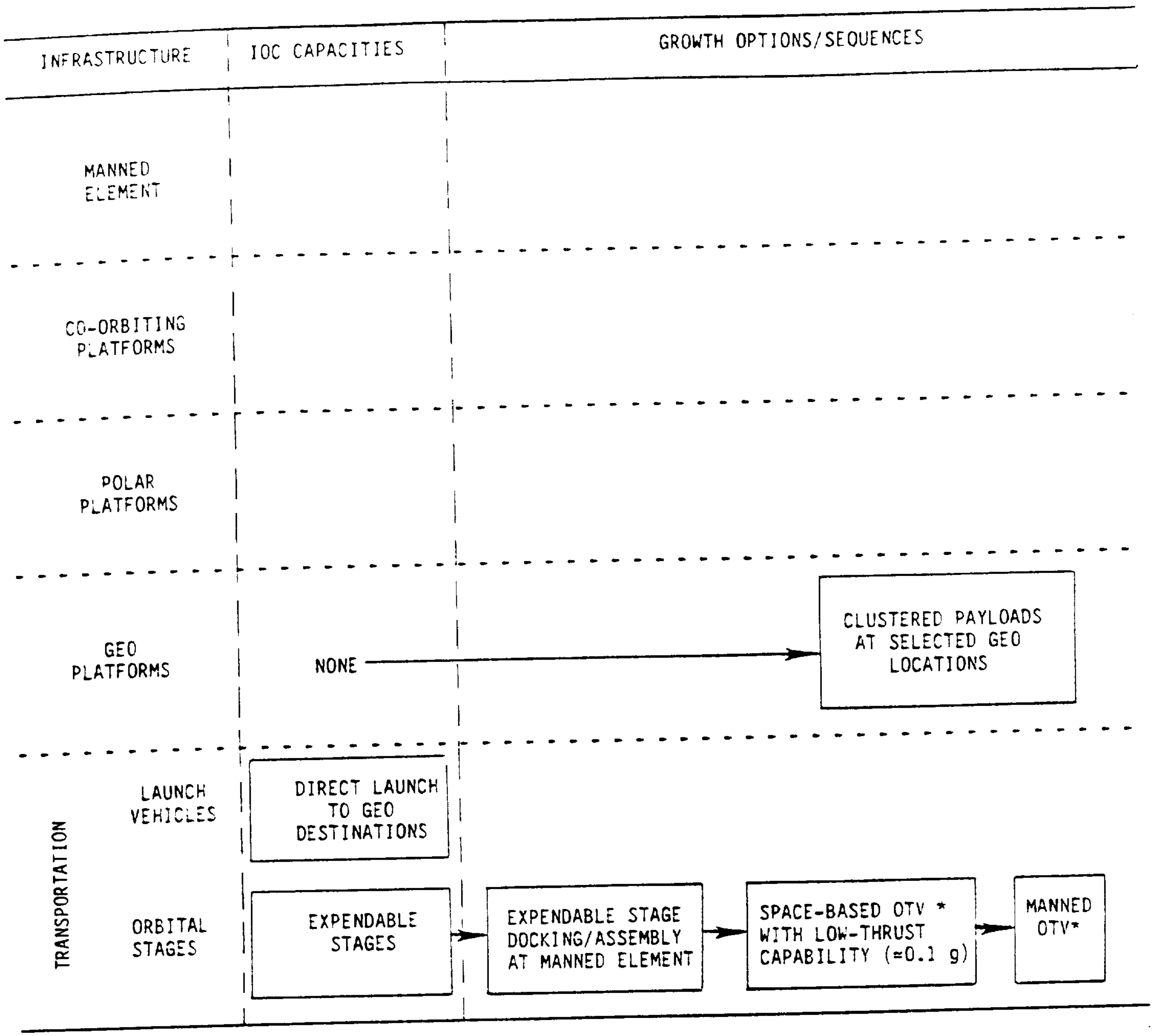


Figure 7. Infrastructure Evolution with Commercial Growth Emphasis: Earth and Ocean Observations

portation and staging node. Early capability for mating expendable stages to payloads at the Station would establish the transportation node function and smooth out Shuttle payload manifests. A space-based reusable OTV, serviced and fueled at the Station, would enable significant staging and transportation functions through the Manned Element as a node.

Commercial growth in Earth and Ocean Observations (EOO) will primarily cause evolutionary changes in the polar platforms of the Space Station infrastructure. The expected changes are depicted in Figure 7. Commercial applications of EOO are viewed at IOC as being principally the purchase of data from science and applications instruments on polar platforms. If the number of instruments remains essentially fixed, the envisioned evolution scenario would proceed with more and more purchase of gathered data as the market expanded. This could lead to policy decisions which would require that science data be purchased from commercial operations, i.e., a reversal of roles (Option 1 in Figure 7). An alternative evolutionary path (Option 2) would entail the addition of commercial instruments to existing platforms and/or the addition of new polar platforms, possibly owned and operated by commercial enterprises. The impact of the first option on the infrastructure would be largely one of policy, i.e., who sells and who buys data. In the second option, operational complexity would increase with increasing platform numbers, as would the demand for STS polar orbit servicing. This would also certainly require the Shuttle polar payload capability to the 32,000 lbm objective and, if possible, improve manifesting to near-maximum levels.

Growth in communications satellite (COMM) activity within the Space Station infrastructure is expected to be largely related to transportation, with the possibility of GEO platforms emerging in later stages of evolution. This scenario is illustrated in Figure 8. No communications satellites launched from the IOC Station are presently included in the data base. As an early evolutionary capability the Team envisioned the assembly of existing upper stages to payloads at the Manned Element. This could be done with a relatively small impact on the Station and could improve overall Shuttle payload manifesting. A next step would be a Station-based reusable OTV requiring development of a new orbital transfer vehicle. Consideration should be given



NOTES: * A SPACE-BASED OTV ALSO IMPLIES MANNED ELEMENT GROWTH ACCOMMODATIONS INCLUDING PROPELLANT RESUPPLY FACILITIES

Figure 8. Infrastructure Evolution with Commercial Growth Emphasis: Communications

to the development of a low-thrust capability ($\approx$0.1 g) for the OTV to accommodate structural limits of large-aperture GEO instruments assembled at the Station. The OTV would have a significant impact on the Station, requiring additional facilities for propellant storage, refurbishment, payload assembly, refueling, and checkout. Commensurate with the development of clustered GEO payloads and platforms could be the introduction of a manned OTV, again based at the Station. This evolutionary step would require further development, additional crew accommodations at the Station, and more consumable replenishment requirements. It should be noted that the probability and extent of manned OTV capability will depend to a significant degree on the advances achieved in platform automation and robotics over the course of these orbital transportation improvements.

A final area of commercialization considered by the Team was industrial services and operations (S/O). Such commercial support could be provided to any one or all of the Space Station infrastructure elements. The IOC Station will be operated and serviced by NASA and its international partners. Alternatives for moving these activities to the commercial sector are presented in Figure 9. A first option would be for NASA to engage contractors to operate the Station. At some point NASA could then spin off its responsibility to other Operational Agencies (e.g. NOAA or DoT) or give the responsibility directly to the contractor, who as a commercial operator would be directly reimbursed by users for services and operations. A second option would be to spin off operating responsibility directly to Operational Agencies and let them work the transition to commercial S/O. The third option would be a direct turnover of Station S/O to commercial operators. Many policy issues need to be addressed before a preferred option for commercializing services and operations can be pursued (if at all). The impact of doing so would be to focus NASA's primary Station role on R&D and let Station infrastructure growth be determined by the economics of nearer-term markets.

IOC Scars. The Team identified several areas of the infrastructure where scarring would enhance subsequent opportunities for commercial growth. Scarring for the provision of additional utilities at both the Manned Element and on platforms was considered essential since large increases in utility

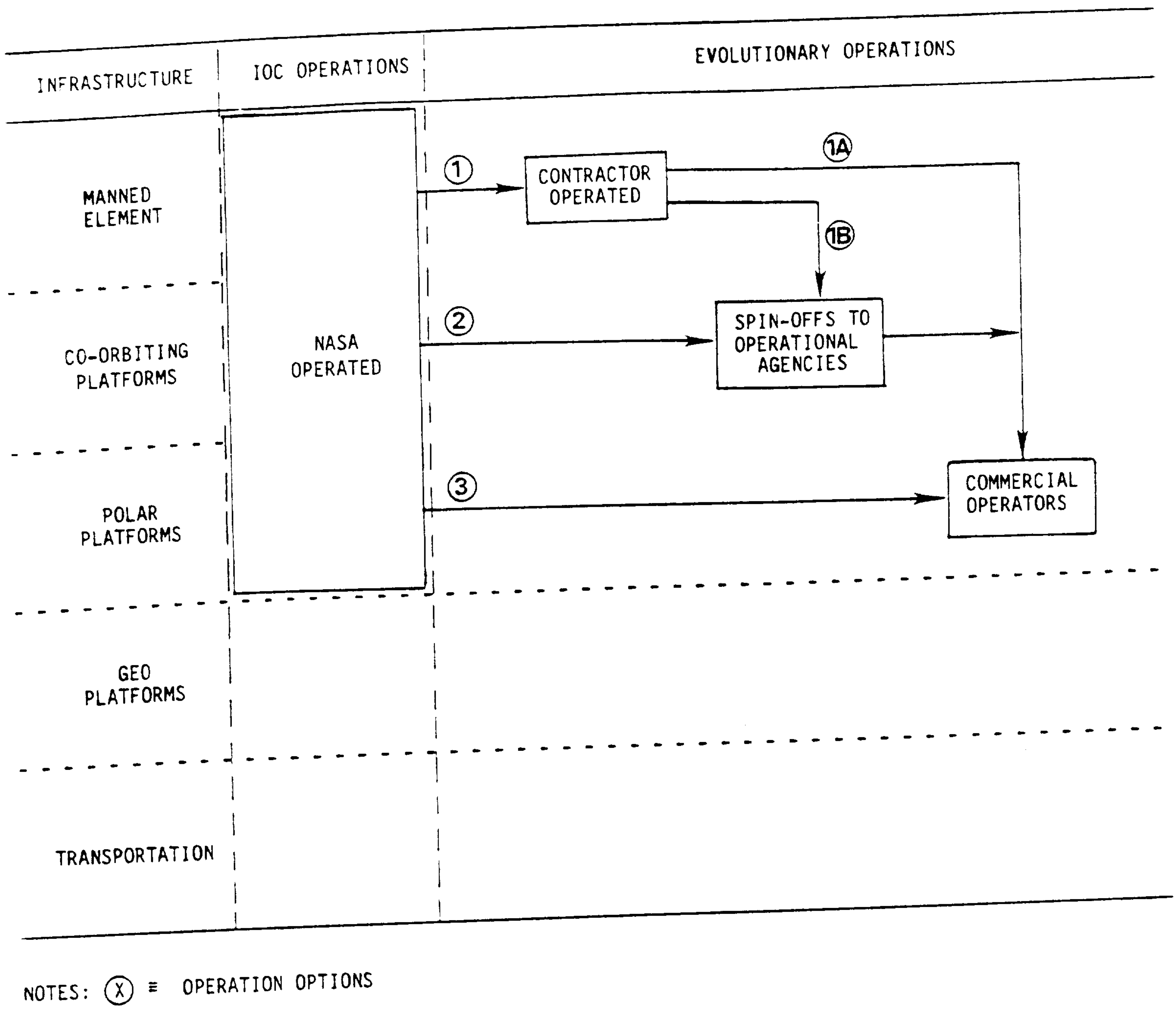


Figure 9. **Infrastructure Evolution with Commercial Growth Emphasis: Industrial Services & Commercial Operations**

capacity are foreseen if space manufacturing reaches production levels. With the proliferation of commercial platforms (or a second station) and GEO COMM payloads, the Manned Element is expected to become a major transportation node. Scarring for this role means anticipating the supply, storage, and management of raw materials, the handling and return of products, and the necessary service facilities for supporting space-based commercial activities. The Team also raised an important infrastructure scar which may easily be overlooked in Space Station design analyses. As a part of the infrastructure, adequate ground facilities will be needed to manage the logistics and information related to the identified commercial activities. The modifications and capability upgrades to current facilities to meet commercial growth need to be addressed.

New Technologies for Commercial Growth. The needs for new technologies and their benefits to commercial growth were recognized by the Team in four evolutionary requirement areas, namely: (1) transportation; (2) logistics; (3) power; and (4) operations. Desired technology advances in each of these areas are listed in Table 9. Several of these identified technologies are similar to those defined earlier for R&T growth (Table 7), namely, OTV-related automation technologies. Others are new, such as the need for new logistics management tools. The table only summarized the more apparent technologies associated with commercial growth. Others will certainly emerge as the prospects for commercialization become better understood.

Trade Studies. Six areas of trade studies were identified by the Team as a result of their discussions of commercially motivated Space Station growth. These are as follows:

1. **Examine the relative merits of the infrastructure growth options identified for each area of commercialization (see Figures 6, 7, and 8).**

   Which options best follow expected mission demand? What are the relative phasing requirements for resources and services? What are the mission impacts of alternative options? Which options minimize barriers to growth for the IOC design? For which options can scarring be most easily accomplished? What are the relative costs to NASA, other agencies, and the commercial sector for the various identified growth alternatives? How do these costs compare to "ability-to-pay"?

Table 9

TECHNOLOGY NEEDS STIMULATED BY COMMERCIAL GROWTH REQUIREMENTS

Requirement	New Technologies
Orbital Transportation	Development of space-based OTVs will require new technologies for the handling and storage of cryogenic fuels and for the refurbishment and maintenance of the vehicle's various subsystems.
Logistics Management	New tools need to be developed commensurate with increases in operational complexity; specialized automated logistics planning and scheduling are two important applications.
	Technology is needed for the safe handling and disposal of large volumes of hazardous by-products of manufacturing.
Power	High power requirements for both the Station and platforms will drive power technologies; the need for nuclear power may arise if substantial commercial growth is to be accommodated at the Station.
Operations	The development of automated, remote servicing capabilities would be a major technology advance, strongly enhancing commercial platform operations; increased automation capability here directly reduces reliance on man-tended operations and associated crew-size growth.

2. **Assess the alternative methods of increasing power.**

What are the advantages/disadvantages of photovoltaic vs. solar dynamic vs. nuclear power sources? How do their relative merits change with power level? Is the choice of power source a function of the infrastructure element? If so, explain. Are there possibilities for co-generation within any of the elements? Are there distinct power thresholds within commercial growth? If so, what are they?

3. **Analyze the trade-offs between increasing crew size and increased automation.**

What areas of support are candidates for increased automation? In these areas, what are the man-loading requirements without automation, and with automation? What new technologies are needed before automation can be applied? What are the economic trade-offs between more crew and more automation in each of these areas? If man-loading is used in preference to automation, how large will Station crew sizes become with data base growth? Where will applied automation provide the largest savings in crew size? What are the safety issues for either approach?

4. **Investigate logistics alternatives.**

Is it more cost-effective to develop logistics warehouses on orbit or to transport logistics on an as-needed basis? Is the choice a function of logistics type? If so, define. Can logistics be managed as a global set for all activities, or must they be managed according to commercial discipline, i.e., how generic is logistics management? How do logistics requirements compete with payload requirements within a four-Shuttle manifest? What alternatives are most cost-effective, e.g., expendable vehicles, more Shuttles, HLLV, etc?

5. **Examine alternative servicing strategies.**

What are the trade-offs between self-propelled platforms and OMVs? Are there any cases where platform propulsion is strongly preferred to in situ OMV servicing? Explain. Should co-orbiting platforms and additional stations be serviced by the STS or the IOC Station? Is this choice dependent on the type of servicing? For OMV servicing, what are enabling levels of automation? What additional automation is strongly enhancing? What OMV servicing requires little or no automation (i.e., strictly teleoperated)? Where should OMVs be based? How do their numbers grow with the number of infrastructure elements?

6. **Explore solutions to commercial policy issues.**

What pricing policies are needed for Space Station commercial applications? What are the pros/cons of these policies? Which are favored and why? What policy approach should be applied to Station usage? What should our policy be on "public access"? How will liability and associated insurance coverage be managed? Since this and other similar expenses will all contribute to a base cost of Space Station operation, how can this cost of doing Space Station business be recovered without becoming a disincentive? How can poorly defined commercial requirements be enhanced to permit adequate planning and accommodation for commercially related infrastructure growth?

4.2.3 Team F: A Major New Initiative

The objective for Team F was to determine probable Space Station evolution scenarios resulting from a major new space initiative. In order to examine a wide range of growth impacts, three specific new initiatives were considered. These were, in order of increasing complexity and Station impact:

1. Unmanned Sample Return
2. A Manned Lunar Base
3. Manned Mars Missions.

Though no attempt was made to define these initiatives in detail, key characteristics of each effort can be summarized as follows:

	Unmanned Sample Return	Manned Lunar Base	Manned Mars Missions
• Vehicle Mass in LEO (lbm)			
- at departure	75K	220K	≤1500K
- upon return	100	60K	135K
• Pre-departure LEO Duration	1 Month	2 weeks	2-6 mos.
• Mission Frequency	every 2 yrs.	monthly	every 2 yrs.

Unmanned Sample Return is considered to be representative of comet, asteroid, and planetary (e.g., Mars) sample return missions. The Manned Lunar Base represents a program which establishes and continually maintains a permanently manned base on the Moon. Such a program would impose a high level of mass throughput and significant transportation operations on the Station. Because the lunar base purpose was not specifically defined, the Team did not consider the impacts on the Space Station of flights returning from the base (e.g., lunar materials for space production) excepting those associated with crew rotation and supporting logistics. The Manned Mars Missions represent a major program of assembly, fueling, and checkout of very large systems in LEO. This initiative might be a single event or it could embrace repeated missions at frequencies as high as once every two years.

Anticipated Requirements. For the limited degree of definition used by the Team to characterize each of the three major new initiatives considered, the dominant growth requirement on the Space Station infrastructure was the need for a comprehensive transportation node. Node capabilities should include adequate payload capacity to LEO, assembly, staging, and checkout facilities at the Station, significant propellant storage capacity for OTV operations, increased crew accommodations, automated OTV recovery of returning vehicles in higher orbits, and certain mission-unique payload handling functions. These requirements are summarized in Table 10 for each of the three new initiatives considered.

For Unmanned Sample Return an increase in STS payload capability to 75K lbm is needed or assembly of orbital stages and sample return payloads (launched separately) at the transportation node is required. If the orbital stage is a space-based OTV it can usually be recovered after the payload is launched into interplanetary space. Propellant storage at the node can be as much as one fully loaded OTV equivalent. For payload mass control reasons, returning samples from these unmanned missions will be captured into higher energy orbits (12 to 24-hour elliptical orbits are preferred). Recovery of the samples to the transportation node can therefore require up to one fully loaded OTV. Upon return to the node these samples are expected to receive special handling, including possible quarantine isolation, special environmental (thermal/vacuum) control, and preliminary laboratory evaluations.

Table 10

POTENTIAL SPACE STATION REQUIREMENTS WITH A MAJOR NEW INITIATIVE

Infrastructure Requirement	Major New Initiative: Unmanned Sample Return	Major New Initiative: Manned Lunar Base	Major New Initiative: Manned Mars Missions
• Transportation to LEO (System Mass)	STS (75K lbm)	STS + HLLV (220K lbm/month)	HLLV & STS ($\leq$1500K lbm/mission)
• On-Orbit Assembly and Checkout	Staging and checkout	Major staging and orbit transfer	Major assembly & checkout (IOC equivalent)
• Propellant Loading	One OTV equivalent	Two OTV equivalents per month	Ten OTV equivalents per mission
• Crew Throughput	N/A	Six or more people "continuous"	6-8 crew members at departure and return
• Recovery Capability From Return Orbit	Ferry capability ($\leq$ one OTV)	Part of manned OTV deployment	Ferry capability ($\leq$ one OTV)
• Other Possibilities	Possible thermal control and isolation of returned sample	None yet defined	Possible readaptation activity on SS upon return

A Manned Lunar Base will require considerably more launch capacity than that available from a four-Orbiter fleet, particularly given the concurrent launch needs of other users (e.g., the DoD, NASA Science and Applications, and the Space Station itself). A Heavy Lift Launch Vehicle (HLLV) capable of lifting 220K lbm to LEO once a month would meet this requirement. Significant staging activities would be required at the LEO transportation node to supply the Base with logistics and crew rotations. Typically, each lunar sortie would require two OTVs, one manned and one unmanned, staged together to perform the transfer maneuvers. Hence, given one sortie per month, the equivalent of two OTV propellant loads would have to be stored and available at the Station node monthly. With crew rotations of about six people the node would also have to accommodate six additional crew members virtually continuously (either outbound or returning from a tour of duty at the Base). No special recovery considerations are apparent at the transportation level for the lunar base, but further definition of operational details would probably uncover additional requirements in this area.

The Manned Mars Missions represent a major buildup of systems in LEO before Earth departure. This is particularly true in the early phase of a Manned Mars Program because there would be little interplanetary infrastructure yet established to assist such missions. Many HLLVs would be needed to accumulate up to 1,500K lbm in LEO for each mission. The checkout and assembly of the various system elements into a complete configuration, including propulsion, would be comparable to the buildup of the IOC Space Station itself. Launch opportunities to Mars typically occur once every 24 to 26 months when the planet moves into favorable phasing with Earth. For a period up to six months preceding these opportunities, orbital preparation would be under way. During this time, the support of six to eight additional crew members would be required (initially for construction of the mission hardware, and later for the Mars crew themselves). A buildup of propellant equivalent to ten fully fueled OTVs would also have to be accomplished during this assembly, along with the delivery of various life-support expendables to LEO. After departure, a hiatus of activity in LEO would occur for two years or longer (depending on mission trip time and the timing of the next Mars mission). Space Station requirements for the returning Mars crew include an

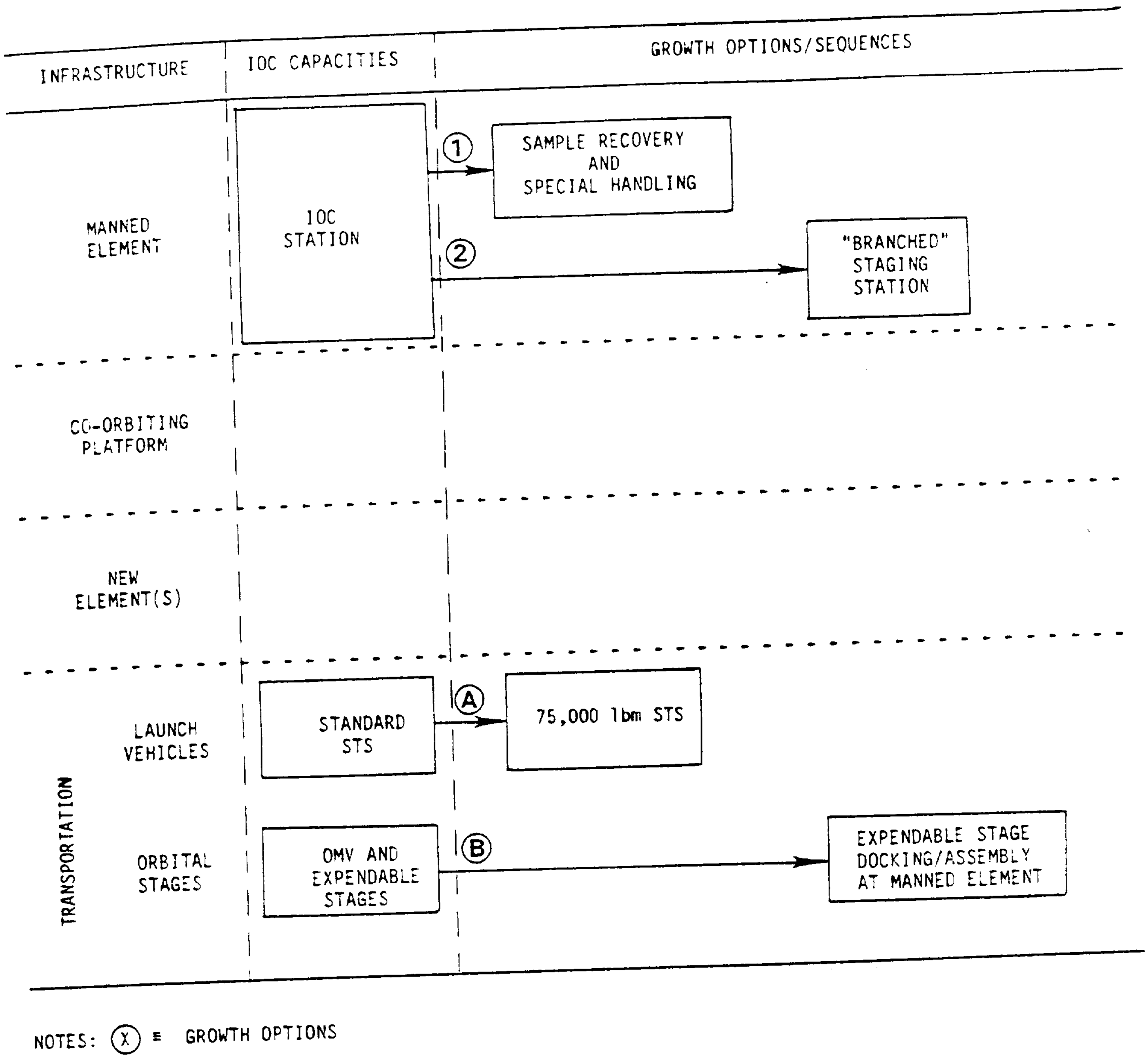


Figure 10. Infrastructure Evolution with New Initiative: Unmanned Sample Return

OTV for orbital recovery and ferry capability to a LEO transportation node. Special equipment and accommodations at the node may also be required for readaptation activities and medical examinations before the crew is able to return to the 1-g environment of Earth's surface.

Infrastructure Growth Options. The Team identified four potential infrastructure options as possibilities for use with each of the three new initiatives it considered, during their on-orbit assembly, preparation for launch, and upon mission return to Earth orbit. In order of increasing evolution from IOC capabilities, these options are as follows:

Option 1: Attachment to the IOC multidiscipline Station.

Option 2: Attachment to a "branched" Station dedicated to operations (servicing, construction, staging, etc.).

Option 3: Free-flying assembly co-orbiting with a Station transportation node.

Option 4: Free-flying assembly unconstrained with regard to the Space Station infrastructure.

For the latter two free-flying options an "assembly system" may be needed to provide certain essential support functions (e.g., stabilization, resources, crew shelter, etc.) for the mission elements and assembly crew. If so, such a system could range in complexity from a truss with attitude-control equipment only to a concept providing all resources and crew habitability. Alternatively, such an assembly system might not be required at all if the mission elements themselves can provide the required function. This would be an attractive assembly approach if LEO assembly times are short (weeks to months) so that the mission system's lifetime is not impaired.

Unmanned Sample Return should be able to utilize either of the Space Station-attached options with minimum impact to the infrastructure, since this initiative is not extremely demanding. These options are depicted graphically in Figure 10. For Option 1, which uses the IOC multidiscipline Station, additional capabilities would have to be added for stage/payload assembly and for sample recovery and handling. These capabilities are assumed to be part

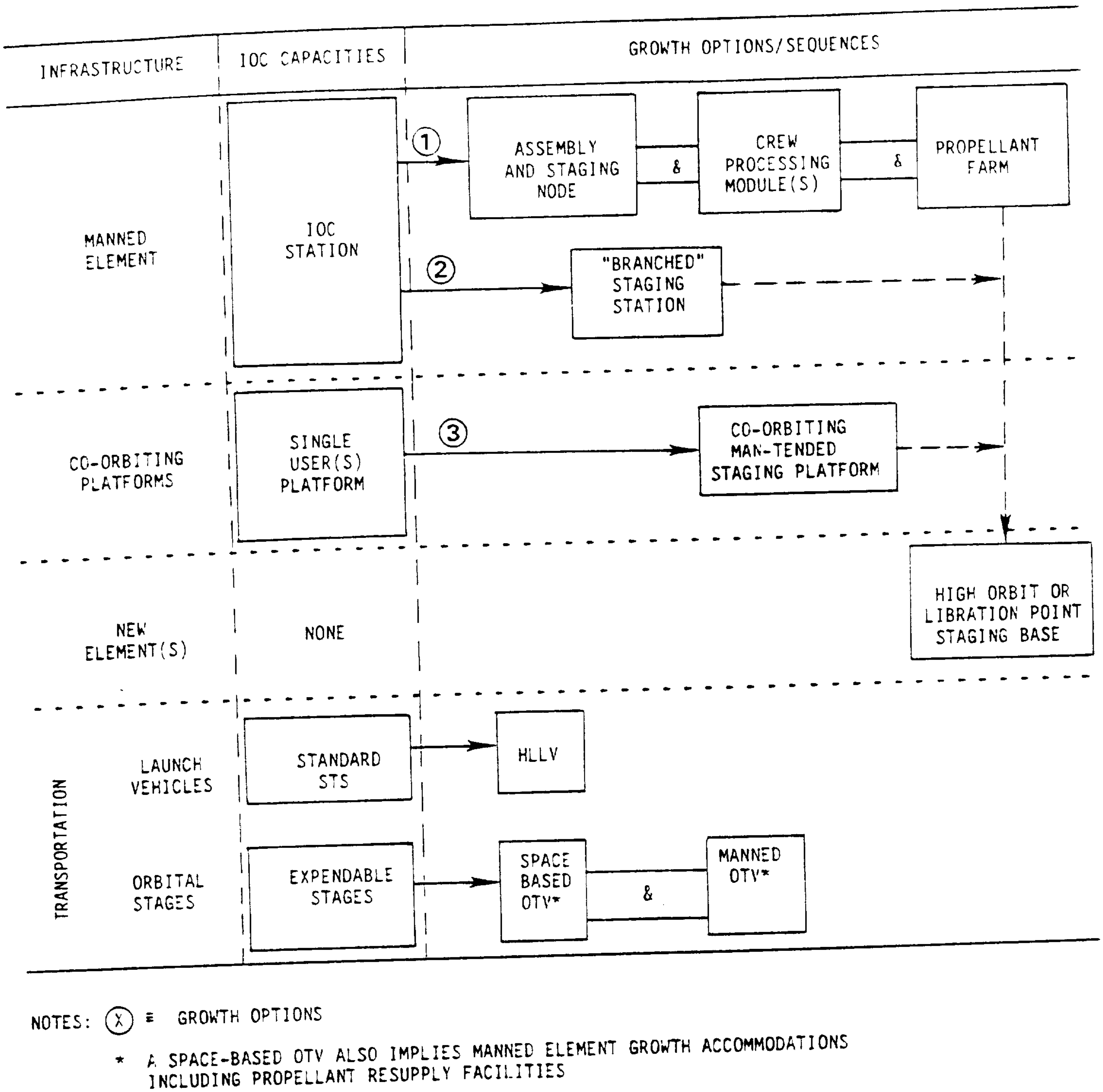


Figure 11. Infrastructure Evolution with New Initiative: Lunar Base

of a dedicated transportation node Station (Option 2). Note also that expendable stages or a space-based OTV is needed at the Station in order to enable these missions, since a 65K Shuttle cannot lift sufficient payload in one launch to meet the LEO mass requirement.

A Manned Lunar Base initiative could be supported by any one of the first three options. These choices, along with transportation requirements, are depicted in Figure 11. Either of the attached options (1 and 2) is possible, but the significant mass and crew throughputs would have an impact on the Station. The launch frequency (monthly) and similar frequency of return elements from the Moon necessitate essentially a continuing level of operations activity at the Station, which would tend to make a branched operations station (Option 2) the preferable choice for this initiative. The specific growth requirements needed on the IOC Station are shown in the figure for Option 1. Option 3, a man-tended co-orbiting platform, is, of course, also a possibility and it would tend to minimize the impact on other infrastructure elements at the expense of a fairly sophisticated platform. Finally, it should be noted that an expanded lunar base with resource mining could provide some portion of the transportation requirements from lunar materials, e.g., oxygen. This could lead to a second high-orbit staging node as part of extended Space Station evolution and it is shown in Figure 11 as a new element of the Space Station infrastructure. Transportation growth requirements for a Manned Lunar Base include an HLLV to launch the necessary mass throughput and unmanned and manned reusable OTVs for ferrying crews and payload between the LEO staging node and the Base.

All four growth options are candidates for meeting the LEO staging requirements of the third and most demanding initiative - Manned Mars Missions. These choices are shown in the evolution chart depicted in Figure 12. The attached Options 1 and 2 are possibilities, but the Mars mission elements can be extremely massive (up to three times as massive as the Manned Element itself) and would have an even greater impact on the Space Station than a Manned Lunar Base. The Mars initiative would impose a requirement on the attached Station for constant operations support for a two to six month period (depending upon capability and availability of heavy lift launch

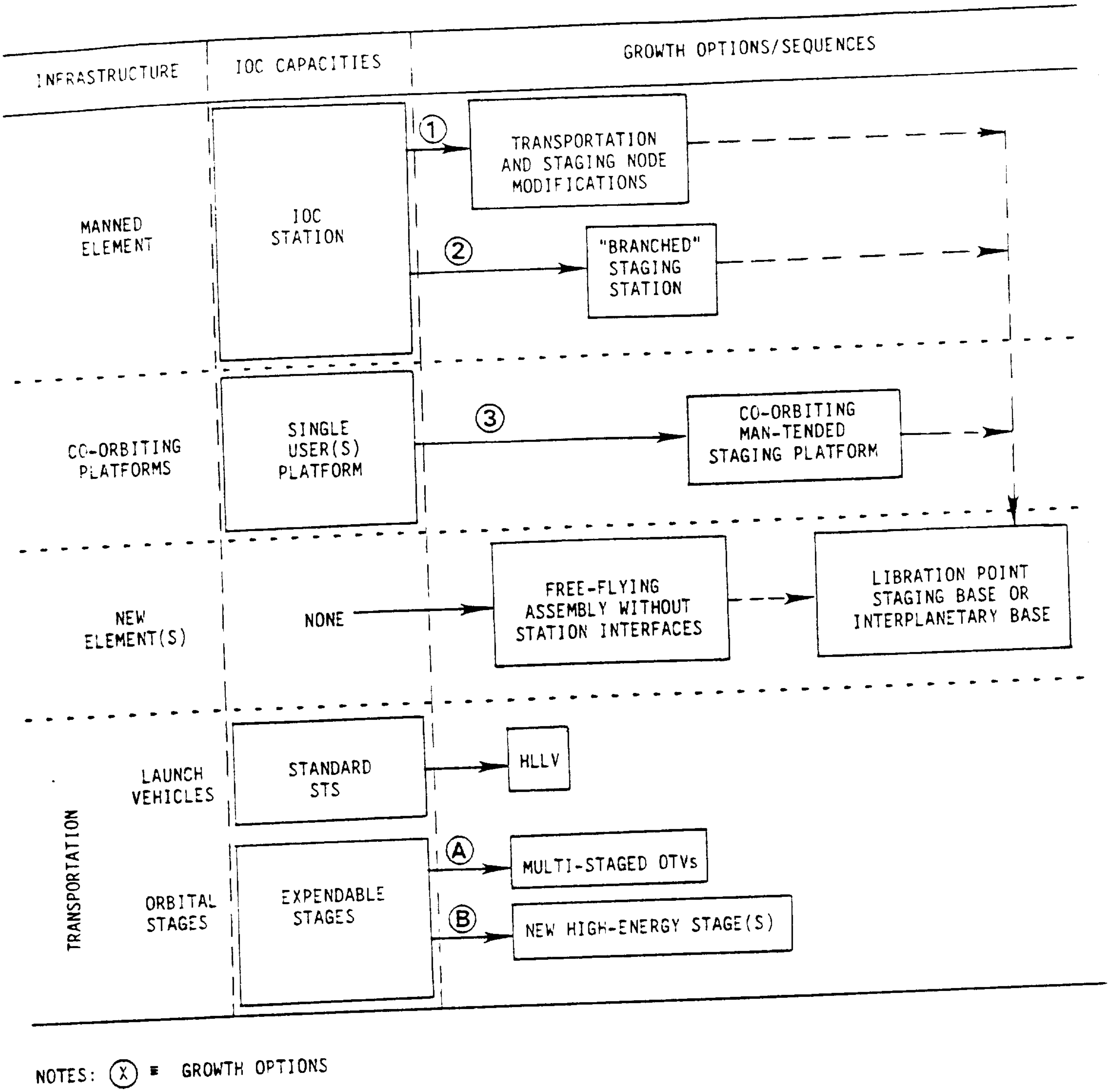


Figure 12. Infrastructure Evolution with New Initiatives: Manned Mars Missions

systems) as often as every two years. Of the two attached options, the impacts would be more disruptive for the IOC Manned Element, thus making a branched operations Station the preferred attached Option. The physical size and resource requirements (power, data rate, stabilization, crew time, crew accommodations, etc.) of the Mars elements may imply that the free-flying options are preferable in order to minimize impacts on other users already committed to the Manned Element(s). The resolution of these choices will require further definition of the Mars Initiative and subsequent trade studies regarding these various impact issues. Note again the need for growth transportation systems in Figure 12, including the possibility of new orbital stages with capabilities significantly greater than those of the OTV. Also, depending upon the scale of the initiative, the creation of interplanetary or libration point staging bases could be added as part of a Mars mission infrastructure. If this were the case, such elements could absorb many of the impacts now expected on the LEO Space Station infrastructure. Such an evolutionary step would probably then favor the attached Options (1 or 2) for the LEO staging.

IOC Impacts and Scarring. A new initiative of the magnitude of a Manned Lunar Base or a Manned Mars Mission would have a profound impact on the Space Station. Either undertaking would involve major activities in construction and assembly, propellant storage and transfer, and general traffic volume. Attachment of a large spacecraft would require a large clear area and extended attitude control capability. Assembly/servicing/pre-launch operations require extensive crew time, mission operations crew accommodations, and "intelligent" automation and telerobotics capabilities. Such smart systems require, in turn, extensive information systems and human operator interface capabilities, e.g., 100M to 1B bytes of real memory per processor, integrated sensor information displays, and natural language interfaces. Neither of these projects has been defined to the extent necessary to predict the operational requirements they might place on the Space Station. Furthermore, the Team felt that a separate specialized Station or a free-flying option would offer significant alternatives as infrastructure branch points to the Attached IOC Station option. For these reasons, changes (scars) to the IOC infrastructure in anticipation of a major new manned initiative (i.e., Lunar Base or Mars Mission) are not recommended.

On the other hand, accommodating Unmanned Sample Return in the Space Station Users Data Base would be an important means of evaluating and validating the transportation node, assembly, and pre-launch functions. Propellant management, complex systems assembly and checkout, and support systems for special assembly crews would all become necessary functional capabilities. A special isolation/analysis facility will probably also be necessary for returning samples as well as for automated orbital recovery. Scarring of the IOC design for these capabilities should be considered.

New Technologies for New Initiatives. There are a number of significant research and technology contributions that the IOC Station can make toward enabling major new manned initiatives such as the Lunar Base or Mars Missions. A preliminary list of items for consideration identified by the Team includes the following:

1. Closure of life-support systems
2. Techniques for the assembly of large structures
3. Design and management of large propellant farms
4. On-orbit test and checkout techniques
5. Advances in automation and robotics
6. Extension of on-orbit maintenance and repair capabilities
7. Development of space-based testing of a wide range of subsystems and module concepts for long-duration manned missions (e.g., electrolysis cells, portable power plants, isolation facilities, automated self-erecting structures, etc.).

In addition to advanced technologies in the systems areas, more work needs to be done on the physiological and psychological limits of manned space travel. This means study of very long-term (more than a year) weightlessness effects, radiation sensitivity and protection, the usefulness of artificial gravity systems, and the analysis of the psychological effects of long-term confinement. Space laboratory ecological and plant life studies are also important. Scarring of the IOC Station may be necessary for some of these efforts (e.g., module wall thickness for radiation studies) and should be given careful consideration in trade studies.

Trade Studies. The Team chose three major new initiatives for which it identified four possible infrastructure options for implementation. A number of issues have been raised in the discussion presented above for the application of each infrastructure option to each new initiative. The process of identifying the best option for each initiative and then selecting the best overall option(s) is presumed to include an assessment of impacts and option responses (scars and upgrades) of the infrastructure. Such an assessment should be performed through trade studies of the various initiatives (including detailed mission definitions) and the ways in which they would employ each of the four infrastructure options to assist in their implementation and operation.

The set of mission elements and activities listed in Table 11 is considered by the Team to be important to such an assessment. The issues of concern for each of these parameters in any specific initiative/option pairing are also given in the table. Trade analyses should be conducted for each initiative by comparing the results of each issue analyzed for each infrastructure considered. These comparisons are expected to lead to a preferred infrastructure option for each initiative. It should be noted, particularly for the Manned Lunar Base and Manned Mars Missions initiatives, that more than one mission design exists. It is fully expected that the identification of preferable infrastructure options could be mission design dependent, leading to mission-dependent option preferences.

In addition to these trade studies, an orthogonal assessment should be performed to understand the flexibility and resilience of any particular infrastructure option to support a variety of new initiatives. A highly responsive option, though not always optimal, could be a better approach than the best option for a specific initiative. The overall outcome of these analyses would be the development of a much higher degree of understanding of the robustness of infrastructure options relative to longer-term initiatives. It is also expected that nearer-term scars and branching criteria will also emerge from these analyses.

Table 11

TRADE STUDIES PARAMETERS FOR DETERMINING VIABILITY OF INFRASTRUCTURE

Element/Activity	Issues
Launch Systems	Mass performance, docking interface, payload sizing
Propellants	Fluid transfer, storage
Physical Accommodation	Attachment, configuration flexibility
Assembly Activities	Logistics buildup sequence, servicing, support requirements
Crew Accommodations	Flight crew, assembly/test crews
Systems Impacts	Scarring and growth for: Attitude/orbit control Power Communications (during assembly) Control management
Ground Systems	Separate vs. shared, unique vs. replicated
Cost	Development -- IOC growth vs. branching Launch -- launch frequency and docking modifications Operations -- assembly, checkout, and deployment

One other trade study of immediate impact to IOC design is recommended. This is an analysis of the modifications and scars required to enable the IOC technology studies relative to future major new initiatives. Should shielding be added to habitat and laboratory modules for radiation studies? What special equipment is needed for the various life science experiments? Are there any practical concepts for creating variable artificial-gravity levels for weightlessness effect studies? What levels of servicing, assembly, and checkout are needed to define and validate the transportation node concept? What crew durations and special accommodations are necessary in support of physiological and psychological studies?

4.3 Session 3: Assimilation of Findings

Three teams were organized to consolidate the findings of the Workshop and draft recommendations with supporting rationale. These teams and their areas of consideration are as follows:

Team G: Near-term trade studies and impacts on scars for IOC

Team H: Longer-term technology development and new scars for technology upgrades

Team I: Policy implications of evolutionary expectations

The results of the work of these teams are presented in the following section of Conclusions and Recommendations, and hence their work is not synopsized here.

5. CONCLUSIONS AND RECOMMENDATIONS

The Workshop findings were assimilated into a summary of possible evolution scenarios, important near-term growth-related trade studies, technology development for longer-term sustained growth, and policy implications of Space Station evolution. The conclusions and recommendations of the Workshop in each of these areas are presented in the subsections which follow.

5.1 Possible Evolution Scenarios

A wide variety of evolution scenarios based on different emphases of growth were developed by the Workshop study teams. These projected scenarios were consolidated into a set of four infrastructure options which capture the essential differences in the posed Space Station evolution alternatives. The four options are summarized in Table 12. Although no specific milestones were set for growth objectives, it is generally anticipated that the posed evolution scenarios are relevant to approximately a decade of Space Station operation. Each infrastructure element is given across the top of the table. Note that three suboptions of growth are given under the Manned Element, i.e., (1) growth within the IOC Station, (2) growth through branching, and (3) growth precipitated by a major new initiative. The four rows of the table correspond to the four different growth options.

Polar platforms are expected to grow to six simultaneously operating platforms in all four scenarios. These platforms, located at different local times, would be needed to support commercial, operational (applications), and research activities. Five to seven co-orbiting platforms of astroscience activities are also expected in each option. Again, these would be operating simultaneously with at least two platforms capable of precise stationkeeping for interferometric observations. Beyond these similarities, the four options differ markedly, particularly in the growth of the Manned Element.

The first option portrays an IOC Manned Element which must grow to meet the full Functional Requirements Envelope (FRE) without branching. It is anticipated that this approach to growth would have to deal with considerable conflict resolution as user operational constraints become less and less compatible.

Table 12

SUMMARY OF SPACE STATION INFRASTRUCTURE GROWTH OPTIONS

GROWTH OPTIONS	POLAR PLATFORMS	CO-ORBITING PLATFORMS		MANNED ELEMENT		
		ASTROSCIENCE	MANUFACTURING	IOC STATION	BRANCHED STATION	NEW INITIATIVE
1	6	5-7		GROWTH TO FUNCTIONAL REQUIREMENTS ENVELOPE	--	--
2A/B				GROWTH IN PRECISION POINTING AND MANUFACTURING	BRANCHED SPACE OPERATIONS	MAJOR GROWTH
3A/B			MANUFACTURING BRANCHED TO 5-8 PLATFORMS	GROWTH IN PRECISION POINTING	BRANCHED SPACE OPERATIONS	MAJOR GROWTH
4A/B				GROWTH IN PRECISION POINTING AND SPACE OPERATIONS	BRANCHED MANUFACTURING	--

The second option retains precision pointing and manufacturing activities on the IOC Station and branches the dynamic space operation activities (i.e., staging, assembly, servicing, etc.) to a second Manned Element. As an alternative within this option, the operations activities could remain with the IOC Station and precision pointing and manufacturing activities could be branched to a second station. The preferred alternative would have to be determined by further trade studies. If a major new initiative were undertaken, this option could accommodate it through major growth of the manned operations element (this is discussed further below).

The third option retains growth in precision operations on the IOC Station, which also continues to support basic R&D activities. As with Option 2, space operations are branched to a second manned element. The significant difference is in manufacturing which, as individual processes mature to production levels, is branched to co-orbiting platforms. From five to eight additional platforms in 28.5-degree orbits would be expected for this purpose by the turn of the century. As with Option 2, the Manned Element branching could be reversed, leading to two suboptions (i.e., 3A and 3B). Major growth could also be accommodated in this option if a New Initiative is undertaken. Also, at some point, manufacturing could be reconsolidated on a third manned station if production-related logistics, servicing, and shared resources justify such an investment (perhaps commercially supported).

The fourth option retains growth in precision pointing and space operations on the IOC Station with some potential conflicts expected. Manufacturing is moved to a second dedicated station. This option probably cannot respond to a major new initiative because of the constraints of precision activities on space operations. Again, two suboptions exist, since either manufacturing or the combination of precision measurements and space operations could be branched to a second station.

The branching of manufacturing to co-orbiting platforms, which contributes to the characterization of Option 3, could also be considered on an as-needed basis with Options 1 and 2 and as an interim measure in Option 4. In these events, the number of platforms would probably be less than the five

Table 13

INFRASTRUCTURE OPERATIONS OPTIONS FOR MAJOR NEW INITIATIVES

Infrastructure Option	Unmanned Sample Return	Manned Lunar Base	Manned Mars Missions
Attached to Space Station	X	X (1)	X (2)
Attached to Branched "Service Station"	X	X (3,4)	X (4)
Free-Flying Assembly, Co-orbiting Space Station		X	X (5)
Free-Flying Assembly, No Space Station Interface			X (5,6)

Notes:
1. Other functional capabilities might not be supportable along with Manned Lunar Base.
2. There may be scenarios which permit direct assembly support by an IOC SS. However, due to inadequate definition of a baseline Mars Mission design, and the apparent attractiveness of other options, it is not appropriate to scar the IOC Station specifically at this time.
3. Launch frequency may require this choice.
4. Sizing of a branched "service station" is undetermined.
5. Physical size and resource requirements may dictate one of these choices.
6. This option may require a dedicated attached assembly system; the Mars vehicle might be used for housing the assembly crew if assembly time is short; stabilization and resources could be provided by a SS-derived truss system, SS LEO platform, or special carrier.

to eight suggested for Option 3. If such a transfer of manufacturing occurred in Option 2, it would become almost equivalent to Option 3, differing only in the degree of manufacturing absorbed by the platforms.

To further define the impact of a major new initiative on infrastructure growth, a matrix of accommodation options versus new initiatives is presented in Table 13. The three initiatives are those posed by one of the Workshop Teams and discussed earlier, i.e., (1) Unmanned Sample Return; (2) a Manned Lunar Base; and (3) Manned Mars Missions. The possible infrastructure options include two attached alternatives and two free-flying possibilities. In all four options the emphasis is on operations requirements, i.e., assembly, staging, checkout, and deployment. The various footnotes to the table highlight issues concerning the various Initiative/Option combinations.

The general conclusion to be drawn from these data is that a major new initiative will have a significant impact on Space Station operations. If the initiative is at the manned level it may be necessary to increase resources and margins (in logistics, assembly area, and control authority) beyond "branched" Station operations in order to adequately support the very significant mission support requirements. This could be a relatively serious constraint on longer-range Space Station applications which will need to be studied carefully in future trade studies. Recognizing the limits of Space Station growth (if they exist) will provide considerable guidance to both its growth and longer-range role in an expanding Earth-orbital transportation and servicing infrastructure.

5.2 Near-Term Trade Studies

The investigative approach used by the teams to analyze the various evolutionary options included identifying: (1) growth requirements; (2) related implementation issues; (3) important trade studies for issue resolution; and (4) IOC scars enhancing near-term growth. These steps are summarized in a set of charts (Tables 14 through 17) for each of the infrastructure elements, reflecting the collective impacts of all evolution scenarios. These elements include Polar Platforms, Co-Orbiting Platforms, the Manned Element, and Transportation Systems. The trades identified in these charts are important near-term study topics, so that IOC design efforts can be favorably

Table 14

TRADES AND SCARS FOR POLAR PLATFORMS

• **REQUIREMENTS**	- Six platforms simultaneously in orbit (for commercial, operation, and research applications)
	- Growth to 20 kw of power each
	- Average collective data rate for polar constellation of 500-600 Mbps
	- In situ servicing
• **ISSUES**	- Increased payload lift capability to orbit
	- Data rates exceed TDRSS single link capability
	- Automated servicing
• **TRADES**	- Determine appropriate balance for data handling considering: - On-board storage - Data compression - Direct broadcast - TDRSS upgrade
• **IOC SCARS**	- Capability to grow to 20 kw system
	- Design for automated servicing (payload design criteria for automated servicing)

effected. Trade studies specific to major New Initiative issues are also addressed in the summary of trade studies which follows.

The important requirements, issues, trades, and IOC scars for Polar Platforms resulting from all considered evolution scenarios are summarized in Table 14. The three key issues foreseen in matching capabilities to requirements are adequate payload capacity ($\approx$32,000 lbm) to polar orbit, elimination of communication bottlenecks, and the feasibility of automated platform servicing. Of these issues, the data bottleneck is specific to the Polar Platforms. A trade study is proposed to determine the right approach to data handling, considering various rate improvement techniques. IOC scars important to the platform design include accommodations for power growth to 20 kw, and design for automated servicing. Automated servicing is particularly important because it will permit instrument changeouts and platform repairs to occur without disrupting overall platform operations (i.e., the platforms can remain functional at their operational altitudes).

Requirements, issues, trades, and IOC scars for Co-Orbiting Platforms are summarized in Table 15. Two key issues are raised: (1) the amount of traffic generated at the Manned Element in support of the many possible co-orbiting platforms (up to 15); and (2) the inability to meet all platform requirements with a single design. Recommended trade studies addressing these issues include an analysis of commonalities between the various specific platform designs, and an assessment of the various platform servicing modes in order to balance operation support requirements between infrastructure elements. An important IOC scar is the inclusion of automated servicing aids in platform design. On the other hand, if platform design has been scarred to enable buildup from a standard set of modular components, which does not appear to Workshop members to be an attractive approach in the light of platform diversity, the removal of such scars warrants further investigation.

The key growth requirements, issues, trade studies and scars for the Manned Element are summarized in Table 16. Two issues stand out, namely, almost certain utilization conflicts with evolutionary growth and the compounding impact of a major new initiative. Utilization conflicts in space

Table 15

TRADES AND SCARS FOR CO-ORBITING PLATFORMS

• **REQUIREMENTS**	- Five to seven science platforms simultaneously in orbit
	- Precision stationkeeping for interferometry
	- Platform separation maintained to centimeters
	- Knowledge of platform separation to fractions of λ
	- Five to eight materials production factories co-orbiting simultaneously
	- power growth to 50 kw
	- environment less than 10^{-6} g's
	- frequent logistics visits
• **ISSUES**	- Traffic generated at Manned Element
	- Incompatibility of all requirements to a single platform design
• **TRADES**	- Commonality between varying designs
	- Balance between servicing modes
	- *In situ* via OMV (automated)
	- At Manned Element (manned)
	- At STS (manned)
• **IOC Scars**	- Delete scars which enable one platform design to satisfy all requirements
	- Design for automated servicing (payload design criteria for automated servicing)

Table 16

TRADES AND SCARS FOR THE MANNED ELEMENT

- **REQUIREMENTS**
  - Growth to the FRE
  - Laboratory for Hazardous Research (new)
    - fire suppression
    - toxic materials
    - genetic research
    - planetary quarantine
  - Support to major new initiatives
  - Tether interfaces (down and up)

- **ISSUES**
  - Conflicts between types of utilization
    - Precision activities (microgravity, fine pointing) versus space operations (servicing, assembly, space basing)
  - Infrastructure impacts to support major new initiatives

- **TRADES**
  - Design and location of Laboratory for Hazardous Research
  - Is branching of Space Station activities viable?
    - Criteria for establishing branch points
    - Who stays, who leaves?
      - o Space operations
      - o Precision activities
      - o Space manufacturing
  - Impacts and benefits of tethers

- **IOC SCARS**
  - Increased resources to meet FRE
    - Power/heat rejection
    - Crew/volume
    - Laboratory/volume
  - Potential scar deletion of IOC Manned Element if branching can be determined early
    - OTV accommodations
    - Resources

Table 17

TRADES FOR TRANSPORTATION SYSTEMS

- **REQUIREMENTS**
  - STS
    - Increased payload mass to LEO (28.5° & polar)
    - Increased returned payload to Earth
  - OMV
    - Support automated in situ servicing
  - OTV
    - Low-thrust propulsion mode ($\leq$ 0.1 g)
    - Support automated GEO in situ servicing
    - Support new initiatives

- **ISSUES**
  - Emergency crew transportation
  - Program constraints imposed by STS payload limits for both launch and return at both ETR (KSC) and WTR (Vandenberg)
  - Use of Centaur/PAM/other upper stages for reaching high energy orbits from Space Station
  - Use of Space Station as a transportation node to maximize STS manifest capacity

- **TRADES**
  - GEO servicing
    - OTV with or without OMV
    - Automated versus manned
  - Transportation node
    - Improved manifesting versus reduced payload capacity to higher altitude orbits

C-2

operations are especially expected as activity levels increase. Functions which will induce motion and changes in mass properties or require large physical accommodations include OMV departures/captures (ten or more per year are expected), MRMS activity, construction and assembly, satellite servicing, propellant transfer/storage, and OTV operations. The proposed trade studies largely address the question of conflicts involving two specific issues (i.e., the laboratory for hazardous research and tethers) and a more fundamental question of how to resolve conflicts before they begin to occur.

This latter study concentrates on the question of infrastructure branching, an important idea raised several times during Workshop deliberations. The results of a thorough branching trade-off analysis will have an important effect on long-range Space Station infrastructure planning. Trade-off studies regarding infrastructure responses to major new initiatives are not recommended until further study of such initiatives provides more technical detail. Trade studies regarding potential technology advancement activities for the IOC Station aimed at enabling or enhancing future initiatives are recommended. These have been discussed earlier (Section 4.2.3), along with several specific scarring issues. IOC scarring is recommended, as a minimum, to be capable of supporting the Functional Requirements Envelope (FRE) for the Manned Element. If branching trade-off results are encouraging, some previously defined IOC scars may be rescinded in favor of early infrastructure branching.

Finally, summarized in Table 17, are the requirements, issues, and trades for transportation systems supporting the Space Station infrastructure during its early evolution. A number of issues are identified, all concerned with deriving more capabilities and benefits from transportation systems. These are reduced to two important trade studies. The first regards the question of GEO servicing. Should it be done with or without the OMV and should it be automated or manned? What are the relative merits, associated development costs, and important operational issues? The second trade study regards the benefits and liens of tying the Space Station (SS) and the Space Transportation System (STS) together in meeting demanding logistic requirements in the coming decades. The SS and the STS are intimately bound together in mutual customer/service roles. On the one hand, the Space Station is a customer of the STS from the standpoint of delivery services, logistics support, supply, crew rotation, initial assembly, and payload delivery and return. On the other hand, the STS can be a customer of the Space Station in terms of on-orbit logistic services for payload disposition and staging opportunities. This has the potential of greatly simplifying and regulating STS operations from the standpoint of the STS as well as the payload manifesting and associated activities. Potentially, the STS could operate on a high-performance routine schedule with considerably greater manifesting flexibility and capacity utilization and shorter stay time, and thereby lower cost. The STS becomes a delivery service and is relieved of many on-orbit obligations.

The impact to the Space Station is that it provides on-orbit functions or responsibilities which are now ascribed to the Shuttle. The overall first order advantage is gained by the criticality of time to the STS (all relative to launch) and the permanent orbital presence of the Space Station. The Space Station must provide on-orbit payload and staging services but it gains the advantage of more frequent supply opportunities. This arrangement would limit the orbital characteristics of the Station (fixed altitude for regular launch opportunities). The transportation node function of the Space Station starts with the STS.

The cost/benefit feature of this type of operation is needed from the standpoint of both the STS and the Space Station. This entails an evolution of the engineering and operational implications from the standpoint of both the STS and the Space Station. The improved manifesting expected from tying the STS to an SS transportation node must also be compared to the reduced manifest capacity resulting from the higher destination orbit of the SS which the STS would have to achieve.

5.3 Longer-Term Technology Development

Beyond near-term trade studies and IOC scarring, an activity critical to Space Station evolution is the sustenance of technology development over the longer term. This is applied research of advanced technologies, which can enable crucial evolutionary steps to be taken in the Space Station infrastructure at the right time. The approach taken here to summarize important technology developments identified during the Workshop team discussions was first to collect all defined growth requirements as functions of infrastructure element, e.g., Manned Element, Co-Orbiting Platforms, Polar Platforms, GEO Platforms, and Transportation Systems. New technology developments were then defined to a meaningful level of detail to satisfy the assembled requirements. These technologies were then summed by discipline to present an integrated technology development program for Space Station growth.

Fourteen specific disciplines were chosen to catalog the various identified technology developments. They are:

- Attitude Control System (ACS)
- Automation & Robotics (A&R)
- Communication & Telemetry (C&T)
- Data Management System (DMS)
- Extravehicular Activity (EVA)
- Environmental Control/Life Support System (ECLSS)
- Fluids
- Manned Systems
- Materials
- Mechanisms
- Power
- Propulsion
- Structures
- Thermal

The summary of integrated technology needs for Space Station evolution is presented in Table 18, organized under the discipline set. Note that the most affected infrastructure elements are also identified in the table for each identified technology need. No effort has been made to prioritize these needs; it is preferred that they be considered part of an overall technology advancement program in support of Space Station evolution.

An evolution scenario posed for Workshop consideration, but not specifically addressed by any team was entitled "Technology Upgrade Emphasis" (see Section 3.3). In this evolution scenario, it is assumed that physical Station growth is delayed indefinitely but new technologies continue to be added to the IOC infrastructure. It is expected that by doing so some evolution could be accommodated through improved efficiency and productivity, and through the adaptation of new operational modes. Without exploring this proposition in detail, a number of technology emphases/insertions were identified from Table 18 which could have a positive evolution effect on a "frozen" infrastructure

Table 18

INTEGRATED TECHNOLOGY NEEDS FOR SPACE STATION EVOLUTION

Disciplines	Technologies	Infrastructure*
ACS	Precision closed loop control for pointing and micro-g stationkeeping	M, CP
	Robustness for g-level mass/inertia perturbations	M, CP
A&R	Servicing	M, CP, PP, GP
	Auto logistics and planning for commercialization	ALL
	Interactive expert systems/diagnostics	M
	Artificial Intelligence	ALL
	"Smart" robotics systems	CP, PP, GP, T
C&T	TDRSS channel capacity expansion (Ku)	M, PP
	High-speed ground computers/high-capacity storage	M, PP
	Possible Ka, W bands and/or optical (TDRSS)	M, PP
DMS	On-board storage and processing (high rate and capacity, e.g. 500 Mbps - 1 Gpbs	PP
	Automated Remote Servicing	CP, PP, GP, T
	- 10 mips -- space-borne VHSIC symbolic processor	
	- 80 megabytes real memory/processor	
EVA	High productivity space-based suit	M
ECLSS	Closed air/water	M
	Waste processing	M
	Long-term ECLSS options	M
Fluids	Acquisition, transfer, and storage	M, T
	Two-phase separators for non-cryogens	M, CP
	Cryogen fluid management	M, T
Manned Systems	Controls displays for human operator interface	M
	Natural language for continuous speech recognition	M
	Sensing and perception	M, CP, PP, GP

*Key: M = Manned Station
CP = Co-Orbiting Platform, PP = Polar Platform, GP = GEO Platform
T = Transportation Systems, i.e., STS, OMV and/or OTV

Table 18 (concluded)

INTEGRATED TECHNOLOGY NEEDS FOR SPACE STATION EVOLUTION

Disciplines	Technologies	Infrastructure*
Materials	Radiation protection	M
	Hazardous materials handling	M, CP, T
	Debris & fire protection	M, T
Mechanisms	Vibration/shock isolation & attenuation	CP, PP, GP
	Mechanization for servicing	CP, PP, GP, T
Power	High temperature solar engines	M, CP
	Nuclear power plant	M
Propulsion	Hydrogen/oxygen propulsion	T
	High performance and long life, e.g., arc-jets and high-temperature resistojets	M, CP, PP, GP
	Biowaste	M, T
Structures	Advanced aerobrake (OTV)	T
	Large-scale structure precision assembly	M, GP
	"Composite" STS logistics system	M, T
Thermal	3-D high temperature, high capacity heat pipes	M, CP
	Coatings	M, CP

*Key: M = Manned Station
CP = Co-Orbiting Platform, PP = Polar Platform, GP = GEO Platform
T = Transportation Systems, i.e., STS, OMV and/or OTV

design. These technology changes and their implications on Space Station utilization are as follows:

Discipline	Technology Emphasis/Insertion	Utilization Implications
ECLSS	Atmospheric trace contaminants removal	Reduction in specifications and cost of materials processing equipment
DMS	On-board data processing and storage	Adaptive fiber-optic network operating system
ACS	Adaptive control	"Robust" activators enabled
EVA	High-productivity space suit	Improved servicing and maintenance capability
A&R	On-board automation/robotics upgrades	Adequate data management system capability and overall productivity increase for fixed crew size

It should be noted that this strategy can apply to an evolution scenario whether it is physically frozen or continually advancing, i.e., being smarter about how we do things (advancing the state of the art) usually means doing the job better and/or for less.

A summary of technology needs for a major new initiative such as a Lunar Base or Manned Mars Mission is presented separately in Table 19. This was done because these needs are presently less well understood (our knowledge base of such initiatives is far from complete) and are driven largely by transportation issues. The technology needs shown in the table are related to requirements/issues of these new initiatives broken down by functions within the initiative. An exception to this is the first function, which relates to early important post-IOC Technology Development Missions which should be undertaken to improve our knowledge base of physiological and psychological effects of long-term space exposure on humans. Such information is crucial to the feasibility of any major new manned space initiative to be considered by our nation. It is expected that other technology needs will be added to this set as our data base of new initiatives expands as a result of planned future studies.

Table 19

TECHNOLOGY NEEDS FOR MAJOR NEW INITIATIVES*

Functions	Requirements/Issues	Technologies
Technology Development Missions for New Initiatives	Quarantine/special handling Long-duration zero-g Long-term radiation exposure	Isolation facility Zero-g data base Hi-Z radiation data base
Launch to LEO	Marginal STS throw weight	Shuttle-derived vehicle (SDV): 200K lbm to LEO HLLV: 400K lbm to LEO
Assembly and Checkout	Dedicated operations for long periods of time	Resources & crew capacity increases ACS and checkout technology
Propellant Loading	Massive quantities ($\approx 10^6$ lbm)	SDV/HLLV capability Cryogen management
Crew Throughput	Lunar Base - continuous (6) Mars Mission - departure/ return (8)	Crew capacity increase Temporary quarters
Return Recovery	Mars Sample Return - elliptical orbit	Smart front-end LEO circularization

*Relevant to Unmanned Sample Return, a Manned Lunar Base, and Manned Mars Missions.

Table 20

POLICY ISSUES RELEVANT TO SPACE STATION EVOLUTION

- TECHNICAL POLICY ISSUES
  - Need for NSTS Manifest/Use Policy
  - Space Station level-of-emphasis on servicing
  - Space Station reliance/requirement for EVA
  - Flight qualification standards for user equipment
  - Contamination/waste disposal guidelines
  - Nuclear power policy (e.g. access, safety, management)

- INTERNATIONAL POLICY ISSUES
  - Agreements must be binding, yet need to recognize evolutionary character of program (changing roles, levels of commitment, liability, etc.)

- OPERATIONAL POLICY ISSUES
  - Space Station Program ownership
  - Pricing policies
  - Crew mix (selection, mix, duration, access, etc.)
  - Public access (commercialization extent)

- BUDGETARY ISSUES
  - Budgeting for IOC scarring
  - Utilization planning/budgeting for Space Station evolution (technological improvements, replication, branching, etc.)

5.4 Policy Implications

Workshop discussions repeatedly touched on policy issues related to evolution of the Space Station Program. One of the teams (Team I) was charged with assimilating and organizing these issues for future consideration. In doing so the Team first established its perception of what the over-arching policy for Space Station evolution is. Simply stated, this policy is that:

> The Space Station design shall facilitate orderly and cost-effective evolutionary growth over several decades in order to: (1) increase basic resources to satisfy user needs; and (2) provide new functional capabilities required by users.

Within this framework, then, policy issues were collected from the various team discussions and organized under the category headings of Technical, International, Operational, and Budgetary. These results are summarized in Table 20. Note that only issues have been defined, with no attempt made to formulate policy. The more formidable challenge of establishing policy was clearly not within the charter of the Workshop. The effort here was to extract, from the technical discussions of Space Station evolution, ideas and issues which might be helpful to the Office of Space Station in meeting its policy-related responsibilities.

APPENDIX A:

Definitions and Concepts

DEFINITIONS AND CONCEPTS

DEFINITIONS

Space Station:
Totality of space-based elements that are provided by the Space Station Program. The initial Space Station includes one manned element, an orbiting maneuvering vehicle, and two unmanned platforms.

Space Station Infrastructure:
Space Station plus all of its ground- and space-based support elements (e.g., TDRSS, STS).

Branching:
A process where one or more user functions are moved off the IOC Station to a replicated Space Station element.

Evolution:
Process of increasing the capability of the Space Station Infrastructure to meet users' requirements or needs.

Growth:
A specific form of evolution deriving solely from a quantitative increase in the Space Station Infrastructure.

Growth Space Station:
Generic term referring to any post-IOC phase of the Space Station Infrastructure derived through growth.

Evolution Emphasis:
User requirements that are the primary drivers for evolution of the Space Station Infrastructure.

Evolution Scenario:
Development of conceptual Space Station Infrastructures required to meet a given set of postulated evolution emphases.

Technology Upgrade:
Addition and/or substitution of new technology to the Space Station Infrastructure.

Scar:
Term used, in the broadest sense, to refer to any aspect of Space Station Infrastructure design that is specifically for the purpose of facilitating evolution of the Infrastructure.

Sensitivity:
Extent to which a specific user activity or a Space Station Infrastructure operational activity would be affected by other user activities or by a given evolutionary scenario.

Replication:
Process of Space Station Infrastructure growth through addition of any elements of a similar design (i.e., not requiring a new design and development phase) as the corresponding IOC element.

CONCEPTS

The IOC Space Station Infrastructure is evolutionary, i.e., it will be designed to evolve in response to user requirements.

Space Station growth will occur in discrete phases designated as Phase II, Phase III, ..., Phase N. The IOC is Phase I.

Evolution emphases are based on the concept that at different times different sets of user requirements will be of priority in determing the future character of the Space Station Infrastructure. For example, the Infrastructure might grow or evolve as a consequence of a national commitment to establish a lunar base.

Evolution scenarios are intended to provide a mechanism for identifying potential scars on Infrastructure design.

APPENDIX B:

Participant/Steering Committee Membership and Affiliations

PARTICIPANTS

Ms. Barbara Askins
Code SED
NASA Headquarters
Washington, DC 20546

Mr. Richard Baillie
Code KC2
Johnson Space Center
Houston, TX 77058

Mr. Jerry Barna
Code 501-15
Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Mr. Gene Beam
Code KA11
Marshall Space Flight Center
Huntsville, AL 35812

Mr. Marc Bensimon
Code SEG
NASA Headquarters
Washington, DC 20546

Dr. David Black
Code SC
NASA Headquarters
Washington, DC 20546

Mr. John Butler
Code PS04
Marshall Space Flight Center
Huntsville, AL 35812

Mr. Dennis Fielder
Code SU
NASA Headquarters
Washington, DC 20546

Dr. Ken Frost
Code 400.6
Goddard Space Flight Center
Greenbelt, MD 20071

PARTICIPANTS (continued)

Mr. Harry Guin
Code AA00
National Space Technology Laboratories
NSTL STA, MS 39529

Dr. Dana Hall
Code SE
NASA Headquarters
Washington, DC 20546

Maj. Paul Heartquist
Code SP
NASA Headquarters
Washington, DC 20546

Mr. Ray Hook
Code 288
Langley Research Center
Hampton, VA 23665

Dr. Earle Huckins
Code 288
Langley Research Center
Hampton, VA 23665

Dr. Joe Kerwin
Code SA
Johnson Space Center
Houston, TX 77058

Ms. Carolyn Kimball
Code SUP
NASA Headquarters
Washington, DC 20546

Dr. Tom Labus
Code 501-15
Lewis Research Center
Cleveland, OH 44135

Dr. Henry Lum
Code 244-7, RI
Ames Research Center
Moffett Field, CA 94035

Mr. John Niehoff
Science Applications Int'l. Corp.
1701 E. Woodfield Road, Suite 819
Schaumburg, IL 60195

PARTICIPANTS (concluded)

Ms. Donna Pivirotto
Code 180-701
Jet Propulsion Laboratory
Pasadena, CA 91109

Mr. Brian Pritchard
Code 288
Langley Research Center
Hampton, VA 23665

Dr. Robert Ried
Code EA
Johnson Space Center
Houston, TX 77058

Mr. Lorne Robinson
Code TX
NASA Headquarters
Washington, DC 20546

Dr. Glenn Smith
Code PD3
Johnson Space Center
Houston, TX 77058

Ms. Mary Jo Smith
Code SUR
NASA Headquarters
Washington, DC 20546

Dr. Edwin Speaker
Code SPB
NASA Headquarters
Washington, DC 20546

Mr. Lee Tilton
Code SU
NASA Headquarters
Washington, DC 20546

Mr. William Tumulty
Code SED
NASA Headquarters
Washington, DC 20546

STEERING COMMITTEE

Dr. David Black
Code SC
NASA Headquarters
Washington, DC 20546

Mr. Ivan Bekey
Code MT
NASA Headquarters
Washington, DC 20546

Dr. Aaron Cohen
Code AE
Johnson Space Center
Houston, TX 77058

Capt. Robert F. Freitag
Code SP
NASA Headquarters
Washington, DC 20546

Mr. Daniel H. Herman
Code SE
NASA Headquarters
Washington, DC 20546

Mr. John D. Hodge
Code S
NASA Headquarters
Washington, DC 20546

Mr. Paul Holloway
Code 103A
Langley Research Center
Hampton, VA 23665

Mr. Robert Marshall
Code PF01
Marshall Space Flight Center
Huntsville, AL 35812

Dr. William Raney
Code SU
NASA Headquarters
Washington, DC 20546